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Santa Fe Institute

1992 Annual Report on Scientific Programs

A Broad Research Program on the Sciences of Complexity

MASTER

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DISCLAIMER

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1. INTRODUCTION

1.1. Current Research

In 1992 the Santa Fe Institute hosted more than 100 short- and long-term research visitors who conducted a total of 212 person-months of residential research in complex systems. To date this 1992 work has resulted in more than 50 SFI Working Papers and nearly 150 publications in the scientific literature. The Institute's book series in the sciences of complexity continues to grow, now numbering more than 20 volumes. The fifth annual complex systems summer school brought nearly 60 graduate students and postdoctoral fellows to Santa Fe for an intensive introduction to the field. On a related front, there are growing clusters of SFI-influenced research at the Universities of Arizona, California at Berkeley, Chicago, Illinois, Michigan, Minnesota, New Mexico, Pennsylvania, and Southern California; California Institute of Technology; Duke University; George Mason University; Rutgers University; Stanford University; and Yale University.

Research on complex systems—the focus of work at SFI—involves an extraordinary range of topics normally studied in seemingly disparate fields. Natural systems displaying complex adaptive behavior range upwards from DNA through cells and evolutionary systems to human societies. Research models exhibiting complex behavior include spin glasses, cellular automata, and genetic algorithms. Some of the major questions facing complex systems researchers are: (1) explaining how complexity arises from the nonlinear interaction of simple components; (2) describing the mechanisms underlying high-level aggregate behavior of complex systems (such as the overt behavior of an organism, the flow of energy in an ecology, the GNP of an economy); and (3) creating a theoretical framework to enable predictions about the likely behavior of such systems in various conditions. The importance of understanding such systems is enormous: many of the most serious challenges facing humanity—e.g., environmental sustainability, economic stability, the control of disease—as well as many of the hardest scientific questions—e.g., the nature of intelligence, the origin of life—require a deep understanding of complex systems.

Despite their broad range, however, the capacity to learn and to adapt is common to many systems on the SFI research agenda. Complex adaptive systems typically comprise a very large number of interacting "microscopic" components whose dynamic behavior is highly nonlinear and generally displays emergent "macroscopic" features. For an appropriately rich set of interactions, the system may be seen to adapt in response to either a specified set of external conditions or, more interestingly, in response to internally generated forces.

The Institute is founded on the premise that there are common principles that determine this behavior. However, one of the most important characteristics of complex systems is that they cannot be studied by determining in advance a set of properties to be examined separately and then combined in an attempt to form a picture of the whole. Instead, it is necessary to examine the whole system, even if the examination is very general, and then encourage the emergence of possible simplifications from the larger structure. Consequently, effective research in this field must combine a broad, general approach with the care and expertise that is more commonly found in the disciplines. SFI's program thus includes specialized studies of parts of complex systems falling within existing disciplines; overarching studies that attempt to define the connections between the important, interdependent parts of complex systems; and integrative studies that describe the shared features of complex systems. The current program at SFI is devoted to the study of the fundamental concepts and shared features of complexity and adaptation and to exploring their presentation in the following areas.

Evolution and Coevolution. Evolutionary, adaptive, and learning mechanisms are essential features of many of the adaptive computation techniques being developed and used at SFI to study complex systems. This intense use of the features of biological evolution (mutation, recombination, and gene linking) has also made it possible to model evolutionary processes themselves and to understand, in detail, how populations evolve under pressures of environmental change and competition. Among the results have been simulations of interspecies competition and population changes, speciation, and shifts between stable and chaotic conditions. A highly provocative result has been the demonstration, in these model systems, that many "catastrophic" events, such as population explosions, crashes, and extinctions, occur naturally as by-products of evolution. Because these systems run in computers, they can be analyzed after the event to see what may have caused the dramatic changes. Moreover, the computations can be re-run, with minor alterations, to explore the causation in detail. In many cases, we see that changes had been occurring steadily in the genetic material (the *genotype*), but only when those changes accumulated to a critical point were they actually expressed in the individual itself (the *phenotype*).

Hidden Patterns in Random-Appearing Data. It is possible to collect and to generate massive sequences of data about long-term complex phenomena, from earthquakes and sunspots to fluctuations in foreign exchange. SFI has pioneered a study of how, using novel computational approaches, it may be possible to extract useful—that is, predictable—information from what appear to be random sequences. The assumption is that if the phenomena are the result of complexity that is deterministic (as is found for many idealized systems under study), then it may be possible to discern patterns useful for some degree of prediction. This field has been made possible because of the confluence of three things: excellent long-term data sets are increasingly available and accessible; modern computation provides ways to process immense amounts of data and, more recently, to apply novel techniques, such as those emerging from adaptive computation, to analyze it; and we now have better understanding of how complex behavior emerges from relatively simple rules in large systems. Much of SFI's work in this field, led in particular by Doyne Farmer, Alan Lapedes, Norman Packard, and James Theiler, is focused on biological data (which is proliferating through large-scale research programs elsewhere) in the expectation that manipulating the data will yield insights into the biological functions that produced it. The other major databases that SFI takes advantage of are in economics, and they provide a convincing means of comparing SFI's modeling efforts with actual market performance.

Adaptive Computation. A main focus of research at SFI is on "adaptive systems"—systems that adapt their behavior over time in response to what has been encountered previously. Many of the complex systems being studied at SFI exhibit this adaptation. Research in adaptive computation concentrates both on building computational models of adaptive systems and on using novel computational methods inspired by natural adaptive systems for solving practical problems. Genetic algorithms, neural networks, classifier systems, and simulated annealing are examples of such methods. As a result of their dissimilarity to traditional computing methods, these approaches have led to a broadening of notions of how information processing takes place.

Artificial Life. SFI's artificial life program was inspired in large measure by the proposition that life is a property of the *organization* of matter, rather than a property of matter itself. Life may "emerge," bottom-up, out of the interactions of a great many nonliving molecules. Christopher Langton's and others' work in this novel field, including the production of highly adaptive "organisms" that live in the silicon of computers, has demanded serious consideration of that proposition and, in turn, has led to fresh thinking about how life may have originated. Other work in this area has focused on the attributes of dynamic, lifelike systems and suggests that life's dynamism, and its evolution, is closely coupled to the degree of complexity or chaos of the system. Langton proposes that the dynamic (evolutionary) processes of life occur in a fairly narrow range between stability and chaos. These topics have proven to be highly stimulating for other researchers at SFI working in nonbiological areas.

Complexity, Learning, and Memory in the Immune System. The mammalian immune system is a classic example of a complex adaptive system—a distributed collection of specialized cells that self-organizes to perform highly complex, predictable tasks. Its size is comparable to the brain, and it is capable of highly sophisticated pattern recognition. Although the individual components live only for days, the system itself has a "memory" that persists for decades. Immunology at SFI has been highly interdisciplinary, and early work has produced insights that apply both to the immune system and to complex systems in general.

Computational Approaches to Genetic Data. A particularly important database is being produced by the Human Genome Project, which in time will make available the complete sequence information for human DNA. The amount of data will be enormous, and it is imperative to find ways to wade through it to find useful information. SFI, under the leadership of Alan Lapedes, has initiated a half-dozen collaborations with researchers elsewhere. Much of that work is devoted to applying computational approaches, particularly neural networks, to the readily available sequence data to predict the detailed structure—hence, the function—of proteins. Other work uses sophisticated search techniques to understand the correlations for RNA molecules between similar physical structures and the corresponding sequences that encode that structure. SFI's reputation for work in this area, and our close cooperation with nearby Los Alamos National Laboratory, the site of the National Genetic Sequence Data Bank, recently attracted funding for a new postdoctoral fellow, Bette Korber, from the Pediatric AIDS Foundation; this work studies patterns in DNA sequences of HIV and other data sets, seeking to understand the mechanism of HIV transmission from mother to infant. As in other SFI studies, the results lead to insight into the target system, refinement of the computational tools, and broader insights into complex adaptive systems.

Evolution of Structures in Neurobiology. This program started at SFI in 1992 with a six-week working group led by Charles Stevens of Salk Institute to create an environment in which theorists and experimentalists could work together. The group was motivated by three things: theory is necessary in neurobiology; theory must relate closely to experiments; and no existing theory has materially changed our understanding of the brain. Yet the fact that theories that make use of general principles are starting to be successful in accounting for common experimental observations indicates a developing maturity in neurobiological theory. A common theme identified by participants as important for theory in the future is the representation of information by the brain, and there was a concentration among the theorists on exploring what is known about visual neurobiology. Many saw techniques for acquiring and handling, in parallel, data from neurons as crucial for the development of neurobiology. SFI expects to expand on this promising beginning in 1993 by establishing working groups organized around the themes of self-organization and self-regulation.

Nonequilibrium Economics and Learning in Knowledge-Based Markets. For these past four years the economics research program at Santa Fe Institute has been building an adaptive, complex, evolutionary viewpoint into the central body of economic theory. The long-term objective of this program is to articulate this new viewpoint—and to provide methods, theories, frameworks, and solutions that will help catalyze this change. The Institute, which has pioneered much of this approach and which has recruited many first-rate economists to participate in its programs and their offspring, is well positioned to lead much of this effort.

Human Societies as Complex Adaptive Systems. Several years ago SFI inaugurated a small program to extend work on complex systems to studies of patterns of social development, as reflected in the prehistoric record in the U.S. Southwest. In the Southwest, where excellent assemblages of archaeological records are available, there appear to be similarities in timing of economic and social changes across a broad range. SFI has seen this as an opportunity to think about the societies as complex systems adapting over time. The resulting research has attracted scientists who are attempting to explain some of the patterns in the context of general models of complex adaptive systems. For example, studies are underway of the influence on village formation of spatial and temporal patterns and variability of food production.

In an allied area, SFI has begun to investigate the extent to which organizations, such as businesses, may function as complex adaptive systems—forming, changing, and learning to adapt as economic, technological, and sociological conditions change. A workshop in 1992 on "Adaptive Processes and

Organizations" led by David Lane and Michael Cohen attracted an outstanding group to begin thinking about this topic, and we intend to establish a formal program to pursue this research in 1993.

1.2 Organizational Structure

Like the topics explored, the research structure at SFI tends to be "self-organizing." Project formats emerge from collaborations among the researchers, and one of the primary attractions of SFI is that these collaborations occur and change easily. This is not a result of any formal requirement, but simply a response to the broad challenges presented by problems in complexity. Throughout this report researchers' names appear repeatedly; workers are listed more than once in association with a variety of different projects.

SFI has no permanent residential faculty. A small core of resident scholars, together with a much larger number of invited visiting scholars, comprise the External Faculty of the Institute. These researchers—about 35 people from institutions throughout the U.S. and Europe—agree to spend at least one month per year at SFI where they work on a varied program of mutually supportive research. Visits may be organized around workshops or working groups or, less formally, around time when one or two colleagues will be in residence to work on a problem of mutual interest. In addition there are typically more than one hundred short-term visitors each year, researchers who ultimately become part of the global "research networks" that enable collaborations started at SFI to continue after people leave. SFI also has a small number of postdoctoral fellows in residence at all times. This flow of scholars through SFI enables loosely organized research groups to form and to reform as topics evolve, enabling participants to remain active in collaborations after they return to their home institutions, and ultimately influencing the course of research on academic campuses.

Within the context of its mutable research interests, the Institute does have a typical, if informal, process for engendering and organizing program initiatives. Ideas for full-scale new projects are typically discussed with the President, the Vice President for Academic Affairs, or a member of the Science Board, the SFI body that oversees the overall direction of the research program. After a project has been approved, normally a steering committee of experts from different fields will be appointed to guide the development of the program. One or more workshops composed of experts drawn from relevant fields is held to discuss the appropriate parameters of the program, to stimulate new research collaborations and to foster networks. SFI supports such networks both directly and indirectly by providing funds and facilities for meetings, acting as a clearinghouse for information and providing administrative support. Finally, in some cases research networks will result in the emergence of a residential research program at SFI.

Work goes on simultaneously in a variety of formats: it proceeds both on and off the SFI campus and includes individual projects, collaborations, research networks, and workshops and symposia. In general there was a trend in 1992 toward longer-duration research visits by scientists and toward the scheduling of Workshops that bring blocs of the SFI research family together for several weeks to review progress and initiate new collaborations.

As mentioned, the overall directions of research, and suggestions about who will be invited to participate, are guided by a 50-person Science Board. The Science Board is responsible for assuring that the appropriate mix of programs is maintained, that the central themes of "complexity" continue to guide the programs, and that the core program remains robust and able to inject new ideas into collaborations and new directions. Its Steering Committee keeps the general work of the Board going during the rest of the year, meeting every other month.

The Institute has begun the process of more fully integrating the SFI External Faculty into the discussions and decision-making processes surrounding the intellectual life at SFI. As as first step, SFI External Faculty were invited to attend the annual Science Meeting in March, 1993.

2. INTEGRATIVE CORE RESEARCH

The Institute's largest single program is designated as "integrative core research." As an incubator for new research initiatives and a home for researchers who are not nominally committed to one of the other programs, it captures the work of most of the full-time postdoctoral fellows, who usually collaborate on several different research projects. The program also includes SFI's most broad-ranging research into the principles that characterize the behavior of complex systems.

2.1 Dynamical Systems

2.1.1 Dynamical Systems with Discrete Degrees of Freedom
M. Nordahl

SFI Postdoctoral Fellow Mats Nordahl's wide-ranging collaborations illustrate the incubative nature of the core research environment at SFI. His work focuses on the relation between computation-theoretical and statistical (physical) properties of systems with discrete degrees of freedom. Such systems provide a well-established laboratory for exploring some fundamental theoretical, computational, and physical properties of complex systems. In 1992 Nordahl worked on:

Computation in Dynamical Systems; Geometrical and Statistical Aspects of Computation Theory

The aim of this project is to develop the connections between physics, dynamical systems theory, and theoretical computer science. Such connections could bring benefits in several directions: discrete mathematics can be useful for dynamical systems through symbolic dynamics; the need to treat physical systems where notions such as continuity, geometry, and probability are important could lead to new insights and concepts in the theory of computation.

As an example, a computation-theoretic classification of patterns in higher dimensions would be useful for describing the dynamics of cellular automata in more than one dimension, and for a possible symbolic dynamics of spatially extended dynamical systems. Some work on such analogies of formal languages has been done in computer science, but the theory is far less developed than conventional formal language theory, Nordahl has studied generalizations of formal languages to higher dimensions (with Cris Moore and Kristian Lindgren). Some inequivalent generalizations of regular languages were previously known; however, to classify CA finite time sets, one needs to introduce a new and more general class of languages, which form the higher dimensional analogue of homomorphisms of subshifts of finite type. Together with other known generalizations (which are subsets of this language class), a hierarchy of regular languages in more than one dimension is obtained.

With Cris Moore he has also investigated more complex classes of two-dimensional languages (where internal states could be a finite number of integers, or a stack), language classes of finite two-dimensional objects, and the undecidability issues involved in extensions to infinite configurations. This work has a number of possible physical applications: it applies directly to the ground states of classical spin systems, we have applied it to quasi-crystals and spin glasses, and we are investigating the relation between structural properties of the ground state and relaxation properties. This work is also relevant to ergodic theory—the language class mentioned above gives rise to two-dimensional subshifts analogous to sofic systems in one-dimensional. Other interesting language classes can be defined by considering growth of objects instead of recognition.

Cellular Automata
With K. E. Eriksson, W. Fontana, W. Li, and K. Lindgren

Spreading Rates and Lyapunov Exponents for Spatially Extended Systems. Spreading rates of perturbations have been measured in numerical investigations of systems such as spin glasses, Ising models and other spin systems, random Boolean networks, and cellular automata. Nordahl has developed an analytic approximation scheme for one-dimensional systems where spreading rates are calculated in mean field theory for symbol blocks of finite length. These methods have been applied both to deterministic and stochastic systems, e.g., to calculate the phase diagram of the probabilistic Domany-Kinzel cellular automaton. Present work focuses on making the connection between spreading rates and Lyapunov exponents (as defined for ordinary dynamical systems) more precise.

Transient Behavior in Spatially Extended Systems. Together with Wentian Li , a program to classify spatially extended dynamical systems according to their transient behavior is being pursued. A first publication contains a study of a particular CA rule (rule 110), where nontrivial power-law scaling is observed, e.g., for average transient times on finite lattices. More general analytic results have been obtained for regions of CA rule space where transient times scale logarithmically. They have also investigated the chaotic repellers found in some cellular automata, and their relation to the transient behavior.

Periodic Orbit Expansions. Predrag Cvitanovic and collaborators have developed the zeta function formalism of Ruelle into a useful calculational tool for classical and quantum chaotic systems. Nordahl's effort in this area has dealt with extensions of this formalism to spatially extended systems, both cellular automata and spin systems. The work on Lyapunov exponents mentioned above relates directly to cycle expansions, in that it suggests how to weight different periodic orbits according to the invariant measure. Applying cycle expansions to statistical mechanics models results in a new approximation scheme different from traditional series expansions of statistical mechanics.

Invariant Measures and Limit Sets. A cellular automaton (CA) can be viewed as a mapping acting on ensembles of sequences, which can be described using formal language theory. We have studied computation theoretic properties of this mapping, and explicitly derived the limit sets for a number of nontrivial systems. A more physical approach is to weight configurations according to their probability of occurrence. In previous work Nordahl and his collaborators have characterized CA finite time measures in terms of probabilistic finite state sources. The class of finite state sources encountered has not been extensively studied in the mathematical literature, and deserves further study.

Reversible Cellular Automata. Reversible cellular automata provide simple model systems where the emergence of thermodynamic behavior from microscopic dynamics can be studied. With K.-E. Eriksson and K. Lindgren, Nordahl has shown that for discrete reversible systems, not only is microscopic entropy globally conserved, but also it is actually the spatial average of a localized quantity obeying a continuity equation. This proves and extends a conjecture due to Toffoli for small perturbations around lattice gas equilibria. They are presently extending this work to systems with continuous degrees of freedom, and quantum systems. This will give us insights into the generalization of dynamical systems concepts such as Kolmogorov-Sinai entropy and Lyapunov exponents to quantum mechanics.

Turbulence
With E. Aurell, P. Frich, and V. Zimin

In collaboration with Valerij Zimin (Houston), Peter Frick (Perm), and Erik Aurell (Stockholm), a Connection Machine implementation of the hierarchical turbulence model constructed by the Perm group (a wavelet transform approach to the Navier-Stokes equations) is being developed. This approach may provide new numerical methods for the Navier-Stokes equations more attuned to the hierarchical structure of the turbulent medium. The project includes both computer implementations and theoretical developments; in particular, they are studying analytic approaches to shell models.

Statistical Mechanics of Random Dynamical Systems

Networks of randomly chosen Boolean functions were first studied by Kauffman as models of gene regulation. When the number of function inputs is suitably chosen, there is evidence that biological scaling relations can be reproduced, e.g., for the number of cell types (attractors of the network) as a function of the number of genes. An extensive numerical investigation of the scaling properties of this model is in progress. In the limit where all functions are connected to each other, the Kauffman model corresponds to random maps of a finite set. Nordahl has introduced a spectrum of new weighted random map models by defining probability distributions in terms of Hamiltonians on the space of mappings of a finite set. In this way a number of interesting phenomena are generated, such as phase transitions between various forms of scaling behavior for average transients and periods.

Evolutionary Approaches to Neural Networks
With K. Lindgren, A. Nilsson, and I. Råde

Together with Kristian Lindgren, Ingrid Råde, and Anders Nilsson, Nordahl has studied evolutionary approaches to neural network design. In particular, they have studied applications to recurrent networks, where conventional learning algorithms are less useful due to excessive computational requirements. They have emphasized methods where networks may increase and decrease in complexity during the evolutionary process, in contrast to standard genetic algorithms, where typically fixed-length symbol string representations are considered. This allows successive refinements of solutions to a problem. They have applied these methods to regular language inference and also have studied more complex problem domains provided by various games. The generalization behavior of the algorithm has been studied experimentally, and they have explored some of the theoretical issues involved in generalizing to an infinite set such as a regular language. They are presently investigating applications of evolutionary methods to statistical inference as well as language inference, and applying recurrent networks to the prediction of protein secondary structure.

Models of Coevolution
With K. Lindgren

In an effort to improve our understanding of the dynamics of many simultaneously evolving species, he has constructed a number of different models of coevolution. In some of these, the interaction between species is based on game theory, and individual genomes, for example, may encode a strategy for the game. In others, the interaction is stochastically generated, e.g., random or spin-glass-like. In both cases, the fitness landscape for a species is a function of the other species present. Mutations capable of changing the genome length make the space searched in the evolutionary process potentially infinite-dimensional.

In a project with Kristian Lindgren, artificial ecologies that derive resources from an external environment have been constructed. The result of a game (such as the infinitely iterated noisy Prisoner's dilemma) determines how resources are distributed. Genomes may encode not only strategies, but also preferences for whom to interact with. Hierarchical food webs emerge from the dynamics; Nordahl and Lindgren have studied their statistical properties and compared them to those of real ecologies.

They have also investigated evolutionary models with spatial degrees of freedom, where complex communities dependent on the spatial degrees of freedom for coexistence are observed, and game theoretic models where the game itself is determined through evolutionary mechanisms.

Studies of coevolution may also lead to improved methods for problem solving—an area which is almost completely unexplored. They are presently studying versions of genetic algorithms where the genetic operators coevolve with the problem instances.

2.1.2 Computational Mechanics
J. Crutchfield

Jim Crutchfield's SFI work is on *computational mechanics*—the intrinsic computation in nonlinear systems. One excellent class of models with which to study the interaction of local computation and information flow is nonlinear, spatially extended systems. Crutchfield's theory and methods allow one to analyze how the latter "implement" complex and potentially useful computation in parallel. Aside from the questions of basic physics addressed, the approach promises practical applications in parallel computation, such as nonlinear adaptive image processing, and improved general theoretical understanding, including trade-offs between information transmission and local computation. In 1992 Crutchfield worked on several related projects in this area.

Spatially Extended Dynamical Systems
With J. E. Hanson

State space structures in high-dimensional systems: Details for this project were provided in the 1991 Annual Report. The results were published as in Hanson and Crutchfield (1992). A practical application appeared in Crutchfield (1992a).

Coherent Structure Diffusion and Pattern Ensemble Stability

Using the tools provided by the qualitative dynamics just described, Crutchfield studied the temporal decay of an attractor's vicinity for a domain-wall-dominated CA. Using selected initial pattern ensembles, state space structures in the high-dimensional nonlinear spatial system can be identified via the resulting decay processes. Vicinity decay breaks into two epochs. The first is governed by ideal diffusive annihilation of the walls and is described by the stochastic dynamics of a random cliff walker. The second decay epoch consists of deviations from the ideal due to accumulated space-time correlations coming from the boundary conditions, lattice size, and the deterministic CA rule. The decay behavior in this regime—considered over a range of lattice sizes—falls into two main classes. The first is a decelerating decay to small nonattracted fractions. The second, more populous, class is a catastrophic decay to very small or vanishing nonattracted fractions. Small amounts of additive noise move all lattices into this second class. The work first appeared as a 1992 technical report and will appear in press in 1993.

Turbulent Pattern Bases for Cellular Automata
With J. E. Hanson

One practical application of reconstructed space-time machines is to use them to "nonlinearly filter" time-dependent patterns to detect propagating coherent structures. Crutchfield has made substantial progress by applying these techniques to cellular automata. Using these methods unpredictable patterns generated by CA can be decomposed with respect to a turbulent, positive-entropy-rate pattern basis. The resulting patterns uncover significant structural organization in a CA's dynamics and information-processing capabilities. With collaborator J. E. Hanson, he illustrated the decomposition technique by analyzing a binary, range 2 cellular automaton having two invariant chaotic domains of different complexities and entropies. Once identified, the domains were seen to organize the CA's state space and to dominate its evolution. Starting from the domains' structures, they showed how to construct a finite-state transducer that performs nonlinear spatial filtering such that the resulting space-time patterns reveal the domains and the intervening walls and dislocations. To show the statistical consequences of domain detection, they compared the entropy and complexity densities of each domain with the globally averaged (nonstationary) quantities. A more graphical comparison was also used: difference patterns and difference plumes that trace the space-time influence of a single-site perturbation. Crutchfield also investigated the diversity of walls and particles emanating from the interface between two adjacent domains.

Wavelet Analysis of a Nonlinear Spatial System

Crutchfield presented evidence that the quasi-periodic oscillations (QPO) and very low frequency noise (VLFN) characteristic of many stellar accretion sources are different aspects of the same physical process: a chain of coupled relaxation oscillators. He analyzed a long, high time-resolution (samples) EXOSAT observation of Scorpius X-1 (over 10 hours). The x-ray luminosity varies stochastically on time scales from milliseconds to hours. The nature of this variability as quantified with both power spectrum analysis and a new wavelet technique, the scalegram, agrees well with a nonlinear map lattice—the dripping handrail accretion model, a simple spatial dynamical system which exhibits transient chaos. In this model both the QPO and VLFN are produced by radiation from blobs with a wide size distribution, resulting from accretion and subsequent diffusion of hot gas, the density of which is limited by an unspecified instability to lie below a threshold. A short summary will be published in 1993.

Computational Mechanics

The first two papers published in 1992 concerned with general computational mechanics appeared in the SFI series.

Semantic Information Processing

This topic was covered in the 1991 Annual Report; one paper has appeared in Crutchfield (1992b).

Thermodynamic Formalism and Large Deviations

Extending classical work on statistical methods for Markov chains to stochastic automata and employing the more modern theory of large deviations, he has developed a "thermodynamic" description of finitary stochastic automata. This gives an improved (and implementable) analysis of the structure of invariant sets for such processes and suggests new quantifiers for Bayesian model learning. This work provides a direct connection between Crutchfield's approach to physical complexity—computational mechanics—and the "thermodynamic formalism" and related work on multifractals found the dynamical systems literature. The results will be reviewed in 1993.

Evolving Cellular Automata to Perform Computations
With P. Hraber and M. Mitchell

The study of how nonlinear dynamical systems support computation involves a number of issues and concepts from different disciplines. In particular, how does computational capability relate to dynamical behavior? How predictive of computational capability are statistical and information theoretic characterizations of behavior? He engaged in a substantial effort to clarify the basic issues revolving around the questions of evolution, behavior, and computation. He performed an experiment similar to one performed by Packard, in which a genetic algorithm (GA) is used to evolve cellular automata (CA) to perform a particular computational task. Packard's original study examined the frequency of evolved CA rules as a function of Langton's parameter, and he interpreted the results of his experiment as giving evidence for the following two hypotheses: (1) CA rules that are able to perform complex computations are most likely to be found near "critical" values, which have been claimed to correlate with a phase transition between ordered and chaotic behavioral regimes for CA; and (2) when CA rules are evolved to perform a complex computation, evolution will tend to select rules with values close to the critical values. Crutchfield's extensive experiments produced very different results. He concluded that the interpretation of the original results was not correct. He also reviewed and clarified issues related to dynamical-behavior classes and computation in CA. The main constructive results of his study were identifying the emergence and competition of computational strategies and analyzing the central role of symmetries in an evolutionary system. In particular, he demonstrated how symmetry breaking can impede the evolution toward higher computational capability.

2.2 Models of Adaptation

2.2.1 Algorithmic Chemistry: Toward a Theory of Biological Organization
L. Buss and W. Fontana

Chemistry is the first level of physics at which interactions between objects are constructive in a virtually open-ended combinatorial fashion. The work of SFI Postdoctoral Fellow Walter Fontana and Leo Buss (Yale) has shown that this constructive aspect in conjunction with a many-body system is sufficient to generate a new level of description with its own phenomenology of organization. The starting point is to view chemistry as basically acting like a calculus: it manipulates formulae.

The objects of chemistry have two aspects: a structure and an action determined by that structure. The action consists in producing, upon combination with another structure, a new structure, which, in turn, determines a new action.

Chemistry, then, becomes a set *O* of objects such that each object in *O* is a map from *O* into itself. This looks harmless, but has consequences when seen from a many-body perspective: that is, when considering a large number of such objects acting upon one another. The result is a dynamical system in which the relations between objects are no longer defined externally to them, as was hitherto the case in dynamical systems theory. As new objects are created, new relations of transformation among objects become possible. The result is that such a system has not only the usual attractors in the space of concentrations, but it simultaneously exhibits "attractors" in a space of relationships among objects. Such attractors are invariant algebraic structures. They refer to them as (functional) organizations. Any conventional dynamical system takes place on such a fixed "organization" which describes the relationships, or incidences, among the variables. The mathematical problem consists in having the right theory—a model—of objects that capture the above abstraction of chemistry. Such a theory, they believe, has existed since 1931. Invented by Alonzo Church, it is known as the λ-calculus. Accordingly, their objects are expressions of the λ-calculus. Together with the specification of a many-body dynamical system, they obtain a minimal model of the simplest organization-constructing device. They have implemented such a model on a computer, and they have demonstrated the existence of organizational attractors. Their original motivation was to lay the foundations of a theory of biological organization. The current dynamical system, therefore, reflects this goal: it is a well-stirred stochastic flow reactor that keeps the total number of particles constant (a "chemostat").

Main Results

Boundaries. Collections of initially random objects eventually generate sets of objects that live on an (infinite) subspace of *O* that is invariant with respect to the interaction among objects in three ways, which we refer to as *boundaries* (closures). We call such a subspace an *organization*.

- Boundary 1 (syntax): The syntactical structure of all objects of the subspace can be described by a grammar. Therefore, the subspace constitutes a formal language, whose grammatical structure is invariant with respect to the applicative interaction of its elements.

- Boundary 2 (algebra): All relationships that result from the interaction between objects can be compressed into a finite set of algebraic laws. These laws completely describe the action of each object within the subspace without reference to the underlying λ-calculus.

- Boundary 3 (self-maintenance): The finite subset that persists kinetically in the chemostat is self-maintaining: that is, every object is the result of some interaction among objects in the system.

Seeding Sets. The organization contains subsets of objects, *generators*, that suffice to produce the entire subspace under cumulative iteration. Moreover, the organization contains sets of generators that are self-maintaining: that is, they regenerate the subspace even under replacement iteration. Fontana and Buss refer to such sets as *seeding sets.* They encode all the information to reliably produce the organization in a stochastic flow reactor. While typically there are many different seeding sets within an organization, these researchers have observed one unique set into which all seeding sets expand. They call this set the *center.* The center contains the canonical constructors: the simplest objects that are capable of generating the organization.

Self-Repair. As a consequence of self maintenance, the system regenerates itself upon random removal of rather substantial parts. This defines one aspect of the stability of such algebraic attractors. The other aspect is given by their behavior towards perturbations.

Perturbations. If random objects are introduced, the organization is, in most cases, not altered. The random object and its products from interactions with members of the organization are eventually diluted out of the system. In some occasions, however, the random object may spawn interactions that result in an additional layer on top of the existing organization: algebraic (and grammatical) extensions. Small perturbations never destroyed an organization, but, if repeated injections of random objects added layer upon layer, these researchers sometimes observed the displacement of previous layers. While their model does not yet have a notion of endogenous noise, as exemplified by imprecise copying of a particular chemical representation of a seeding set—DNA or RNA—and, while it lacks, as yet, a notion of reproduction, it nevertheless suggests that their organizations are *evolvable.*

Higher Order Organizations. A highly interesting phenomenon in their model is the spontaneous generation of organizations composed of organizations. This illustrates the power that resides in constructive interactions. When two organizations, A and B, are brought into "collision" by simple interaction among their members, two cases can arise from an algebraic point of view:

1. The union of A and B is closed with respect to the interaction between the elements of A and B; this is observed to result in kinetic competition, leading usually to the displacement of one of the two organizations, depending on the actual network of transformation pathways.

2. The union of A and B is not closed with respect to interaction; this results algebraically in a new organization, C, that contains A and B as subalgebras.

Their experiments show that the additional subspace built by A and B does not exhibit self-maintenance. C-A-B does not qualify as an invariant organization, either syntactically or algebraically; it cannot persist in isolation. They call it the *glue.* The glue is generated by interactions among elements in A and B. Interactions, occurring within the glue itself, generate both more glue and a flow of elements back into A and B. The observed overall kinetic consequence is to effectively dampen competition by buffering and, hence, to stabilize the coexistence of A and B: a super-organization stably containing two component organizations plus a glue metabolism has arisen.

Such a scenario is facilitated and stabilized by imposition of additional boundary conditions, such as different schemes of interaction between organizations than within organizations. This, however, is a technicality. The emergence of super-organizations has been observed and tracked from "zero": that is, from initially random collections of objects, without the imposition of any additional boundary conditions.

Properties of super-organizations are analogous to those of organizations, with the exception that they contain potentially autonomously evolvable units.

This research can be misunderstood in a fundamental way: if taken to be a claim of how chemistry works. The work is evidently not a theoretical chemistry, nor is it a theoretical biophysics. It is, however, a claim about what chemistry does.

2.2.2 Adaptation to the Edge of Chaos
S. Kauffman

The core issues of Stuart Kauffman's work in 1992 concerned the relation between self-organization and selection in biological evolution. Reasonable evidence now suggests that powerful self-organization may underlie prebiotic chemical evolution and the origin of life itself. Related properties of self-organization may underlie the fundamental, ordered, homeostatic properties of development from the zygote to the adult. Similar principles, with rather surprising implications, may apply to the coevolution occurring in ecosystems. In the origin of life problem, self-organization and selection may account for the expected emergence of collectively autocatalytic molecular systems. Hence the emergence of life may be more probable than supposed. Further, the combination of self-organization and selection, operating at the dawn of life and even now, may pull coevolving communities of self-reproducing molecular systems to a newly transition between subcritical and supracritical behavior. Cells may be metabolically subcritical while the biosphere as a whole is probably strongly supracritical. Coevolving cells that form local communities may evolve to the subcritical-supracritical boundary in a manner that governs the metabolic generation and propagation of small and large avalanches of novel kinds of molecules throughout the system. If this should prove true, it would provide a new framework to analyze the impact of novel molecular species released into a community and the responses of the community to those stresses. At the level of the individual and the ecosystem, the marriage of self-organization and selection may pull the adapting genomic regulatory systems underlying ontogeny, or adapting coevolving populations, to a phase transition between dynamical order and chaos.

If these hypotheses prove true, they will profoundly increase our understanding of the propagating consequences of the introduction of thousands of novel chemicals into the environment, of the genetic origins of homeostasis within organisms, and of the buffered sensitivity of ecosystems. The phase transition regime, whether between subcritical and supracritical metabolic behavior, or between ordered and chaotic dynamical behavior, is both buffered and poised. Small perturbations unleash small or large avalanches of change which propagate through the system. The expected size distribution of avalanches is a power law with many small avalanches and few large ones. At the level of the cell, adaptation to the edge of chaos implies that molecular signals altering the activity of single genes can unleash small and large regulatory cascades altering the activities of other genes and molecular variables in a coordinated way, without triggering chaotic behavior. At the level of coevolving organisms, adaptation to the phase transition implies that the same small-scale perturbations can unleash tiny or vast cascades of metabolic or morphological changes which propagate through the system causing, among other consequences, the extinction of old molecular and organismic species and formation of new ones. If ecosystems naturally attain the edge of chaos, our very notions of "sustainability" may require rethinking. Ecosystems may be poised, forever changing, in a characteristic stationary state, but not "stable" at molecular or community levels over appropriate, long time scales.

Kauffman's work in this area has several foci. First, he is exploring two candidate general principles about the internal structure and behavior of complex adapting systems: (1) optimal complex computation and adaptation in parallel-processing systems occurs at the edge of chaos, and (2) under natural selection, adapting parallel-processing systems attain the edge of chaos. He is also examining a proposed general principle governing coevolution that postulates that complex adaptive entities modify their internal structure and couplings to other adapting entities such that the entire system coevolves to the edge of chaos. He is studying the new hypothesis that in coevolving communities, cells or single organisms are metabolically subcritical while the community can be subcritical or supracritical as a function of species diversity and the diversity of novel molecules introduced into the community. In subcritical systems, the generation of molecular novelty in the system following introduction of a novel molecular species is very limited. In supracritical systems the generation of new kinds of molecules is explosive. Increase in species diversity or the diversity of novel molecules introduced into the system may drive ecosystems from subcritical to supracritical behavior. Finally, he is exploring the possibility that natural evolutionary dynamics causes communities locally to coevolve to a phase transition between subcritical and supracritical behavior. Briefly, supracritical communities should rapidly generate many novel molecules, some toxic to some species, causing local extinctions which drive the system toward the subcritical regime. In-migration of metabolically novel species, or evolution of new species, should increase species diversity and, hence, drive the system towards the supracritical regime. He will assess whether these processes generically balance at a phase transition. If true, this could be a general law governing the generation of molecular diversity in the biosphere.

2.3 Measuring and Predicting Complexity

2.3.1 Characterizing the Complexity of Dynamical Systems
Cris Moore

SFI Postdoctoral Fellow Cris Moore's research interests focus on characterizing the complexity of dynamical systems and on the question of the Church-Turing thesis; specifically, how can computation be embedded in physical systems, and can any physical systems perform computations that a digital computer cannot? Moore worked on the following projects and papers in 1992.

Complexity of Two-Dimensional Patterns (in progress)
With K. Lindgren

There is a well-understood body of theory, the Chomsky Hierarchy, for ranking the complexity of "languages", or sets of one-dimensional sequences of symbols. This work is an attempt to define a similar hierarchy for two- or more-dimensional arrays of symbols.

Many subtleties arise. In one dimension, deterministic and nondeterministic finite-state automata are equally powerful; in two or more, nondeterministic automata are more so. In one dimension, local rules lead to trivially solvable languages; in two or more, they can lead to undecidable or NP-complete problems. In one dimension, growing or recognizing a pattern are roughly the same process; in two or more, these two types of complexity, one "dynamic" and the other "static," are very different. For instance, there are two-dimensional "languages" which are easy to recognize but hard to generate, and others for which the reverse is true.

The collaborators feel that this work has useful applications in the areas of cellular automata, image recognition, and the design of parallel computing architectures. Overall, it helps us build an intuition about how information can be conveyed and coordinated from one part of a structure to another; what can be achieved with purely local rules, and what structures or behaviors require long-range interaction and memory.

Braids in Classical Gravity (submitted to Physical Review Letters*)*

In this paper, he considers periodic motion of n particles in the plane, attracted by a power-law potential $V \sim r^{\alpha}$. A periodic orbit of the system can be topologically classified as a braid of n strands; the set of all braids that exist for a given α then constitutes a "language," in analogy with the symbolic dynamics of low-dimensional systems.

To find the solutions, he uses an action-minimization technique; starting from a fictional path of the desired topology, he "elasticizes" the path and seek an actual classical trajectory in the same equivalence class. For $\alpha \leq -2$ (i.e., a $1/r^3$ force), all braids exist. As α increases, braids cease to exist; each one has a critical α at which one particle collides with another, and the braid snaps. Many also have a lower critical α at which the orbit goes from being unstable to stable. Finally, at $\alpha = 2$ (a spring potential) the problem becomes linear, and only "harmonic" braids exist, in which all winding numbers are +1 or −1. This is an example of a high-dimensional "bifurcation diagram" that many systems of the same type can be expected to have. This topological approach to many-body systems is, Moore thinks, a good way to classify the dynamics of high-dimensional systems, which are usually only very clumsily addressed by the traditional symbolic dynamics approach. By associating trajectories with natural, continuous topological objects instead of discrete symbol strings, we can capture the system's behavior in a way that doesn't require drawing arbitrary boundaries in the phase space.

Computation on the Reals: A Model of Analog Computation (in progress)

Traditional computation theory provides a solid framework for discussing discrete problems and functions on the natural numbers. But many physical problems deserve an intrinsically continuous approach: not all problems are best discussed by first encoding them as a series of bits.

In this work, Moore develops a theory of computation in continuous space and time, starting by defining a class of "recursive functions" on the reals analogous to the class of the same name on the naturals. This class turns out to be surprisingly powerful, including both the arithmetic and analytic hierarchies of traditional recursion theory, including infinite sets of problems considered "undecidable" or "uncomputable" in the traditional sense.

However, when looking more closely at these functions and at actual physical realizations of the abstract machines that would calculate them, we find an interesting hierarchy. At the lowest level are smooth functions such as polynomial and trigonometric functions that a simple physical system could calculate "exactly": that is, we could calculate them by integrating a simple dynamical system. At the next level are functions like the delta function ($\delta(x) = 1$ if $x = 0$, and 0 otherwise) which can only be calculated in the limit. (This limit could be infinite time, infinite accuracy; a thermodynamic limit; or an infinite number of ensembles in the quantum case.) The next level up, like a characteristic function for the rationals ($Q(x) = 1$ if x is rational, 0 otherwise), or solving the Halting Problem for a Turing machines, require two limits, and so on.

The interesting thing is that, in practice, we claim to be able to take this kind of limit in physics all the time. For instance, when we calculate the critical exponent of a statistical mechanical system, we take three limits: we take a limit of systems arbitrarily close to the phase transition, each of which has to be taken to a thermodynamic limit and an infinite-time limit. So this calculation would seem to be several levels up in this hierarchy.

By following this theory through, then, we clarify the notion of what is "physically computable," and produce a hierarchy of harder and harder computations, requiring that we carry them out in a more and more idealized world. In this way we partially address the physical Church-Turing thesis: namely, is the physical world computable? Or can it perform computations that a Turing machine cannot? That is, is analog computation any more powerful than digital computation? The answer is that it is, but only in an idealized, classical world of perfect preparations and measurements. In the real world, limited by quantum effects and the Planck scale, we can probably do no more than a traditional Turing machine.

Algebraic Cellular Automata (in progress)

In this paper, Moore looks at cellular automata (CA) whose rules correspond to binary operations with a variety of algebraic properties, such as associativity, commutativity, and various identities like $(ab)(cd) = (ac)(bd)$. Beyond the simple group structure of "additive" CAs, there turn out to be many interesting examples of CAs that are nonlinear but nevertheless more predictable than an arbitrary CA.

For instance, given an initial row of length L, we can ask how much computation is required to deduce the state $L - 1$ steps later, at the bottom of the space-time triangle that follows from that row. In general, this will take L^2 steps, as we fill in the entire triangle; but, for these CAs with simplifying algebraic properties, we can predict the outcome in only L or L^a where $a = (\log 3)/(\log 2) < 2$ steps.

We find that scaling and fractal behavior can be generalized beyond linear examples to simplify prediction, and that "principles of superposition" based on semigroup structures can be more general than the usual kind of "additivity." We also derive some beautiful new types of Green's functions from vector-valued CAs, where the CA is defined by a set of matrix coefficients. Overall, we extend the class of CAs for which an efficient prediction algorithm exists into the "nonlinear" regime.

Smooth Maps of the Interval and the Real Line Capable of Universal Computation (SFI Working Paper)

This extends earlier thesis work in which Moore constructed smooth two-dimensional maps and three-dimensional flows whose action simulated a Turing machine. The long-term behavior of such systems is therefore undecidable; since questions like "will point x ever fall into basin A" or "is x periodic" are equivalent to the Halting Problem, there is no algorithm to answer them, even if the map and the initial conditions are known exactly. This helps to distinguish the information-based unpredictability of "chaos" from the complexity-based unpredictability of systems capable of high-level computation.

In this paper, Moore constructs two classes of maps in one dimension capable of the same thing: once-differentiable maps in the interval (which can simulate cellular automata or the "generalized shifts" of his thesis as well as Turing machines) and analytic maps on the real line, which can be written in closed form as a finite sum of terms of the form $x \sin x$. Although these maps are fanciful and almost certainly unphysical, they further illuminate how computation can be embedded in low-dimensional dynamical systems.

2.3.2 Algorithmic Complexity
C. Caves

SFI Visiting Professor Carlton Caves is working on the growth of algorithmic complexity in perturbed classical chaotic evolution and perturbed quantum evolution. Initial work has focused on chaotic two-dimensional maps and their quantum analogues, the goals being to assess the characteristic behavior of algorithmic complexity under perturbations and to investigate the connection between classical chaos and quantum mechanics. A more ambitious task would be to analyze realistic examples of perturbed phase-space evolution or perturbed quantum evolution in terms of stochastic Liouville equations or stochastic Schrödinger equations.

Analysis of the growth of algorithmic complexity in dissipative dynamics accessible to experiments in quantum optics. The goal here is to model the perturbation of a quantum system in terms of interaction with a reservoir in the usual manner of quantum optics and thus to relate standard approaches to quantum dissipation to the rate at which algorithmic complexity grows in such models.

2.3.3 Measures of Complexity
M. Gell-Mann and S. Lloyd

Seth Lloyd's research centers on the role of information in complex systems. He is investigating both how existing physical and biological systems process information, and how to employ nanotechnology to create new systems whose information-processing capacity can be directed and put to use. With Heinz Pagels, Lloyd developed information-based measures of complexity that can be applied to any physical system. He is currently applying these measures to "smart" engines—heat engines coupled to computers or microprocessors—to show how limits on the ability to process information translate into limits on thermodynamic efficiency. He is using these measures to gauge the adaptive ability of populations undergoing natural selection and to compare the information-processing power of populations of bacteria and viruses with the information-processing resources that the immune system marshals to combat them.

In addition, with Murray Gell-Mann, Lloyd is using information-based techniques to characterize how and when fundamentally quantum-mechanical systems exhibit classical behavior. When can a quantum system compute? Current proposals for quantum computers rely on "designer Hamiltonians," that do not correspond to any real physical system. He is currently investigating physically attainable quantum effects that could be exploited to create nanoscale quantum-mechanical logic gates. In a search for realizable quantum computers, he has derived necessary and sufficient conditions on the spectrum of a quantum-mechanical system for that system to possess observables whose time evolution is that of the logical states of a digital computer.

At the same time, Lloyd has shown that the spectral decomposition for a quantum system is of little practical use in actually making the system compute, since deriving the computational observables from the spectral decomposition is as hard as solving the hardest problem that the computer can solve. He is currently working on a technologically feasible scheme for quantum computation, in which weakly coupled quantum systems, such as localized electron states in a polymer or quantum dots in a homogeneous array, process information when clocked by resonant pulses of light. Such a computer could be used to perform parallel computations on high information densities (one bit per nanometer for a polymer computer, or one bit per tens of nanometers for a quantum dot computer), at high clock speeds (tens of picoseconds for visible light), and to create novel quantum states.

2.3.4 Complexity in Adaptive Systems
W. Macready

Titles of papers in the new science of complexity often include the phrase "complex adaptive systems," and yet the relationship between complexity and adaptability remains an open question—one which is the focus of postdoctoral fellow Bill Macready's research.

The first step toward characterizing the relationship between complexity and adaptability is to find an appropriate measure of complexity. We do not think of orderly patterns as being complex because we can describe them with very little information. We might think of disordered or random patterns as being complex, but actually their statistical properties can also be described with limited information. It is only the patterns at the "phase transition" between order and disorder which are hard to describe and it is these we call complex.

Macready is exploring the adaptability inherent in systems which are "living at the phase transition," as well as how adaptation can drive a system to this complex region. One definition of adaptability is the ability of a system to respond to a variety of constraints with minimal changes in its structure. Using such a definition, it is not entirely clear that adaptable systems are necessarily complex ones. If we ask a system to adapt to a particular set of immutable constraints, we do not necessarily expect the system to become complex. In fact, we might expect the system to lower its complexity and solve the constraints in the simplest possible way. Thus we might expect the complexity of a system will only increase if we ask the system to adapt to a changing environment.

It is Macready's aim to prove, by direct experimentation and independent of any particular model, whether or not complexity is an inherent characteristic of adaptive dynamical systems. Specific instances of dynamical systems are ubiquitous in nature, and dynamical models of natural systems include cellular automata, neural networks, and Boolean network models of molecular evolution. A generic dynamical system is obtained by referring only to the state transition graphs without attaching any meaning to the states themselves.

These generic systems are then asked to evolve in order to solve a constantly changing task (again defined without reference to a particular model). If complexity is a necessary feature of adaptive systems, then we expect to evolve systems in the complex or ``phase transition'' region between order and disorder. However, if these expectations are not borne out, it will call into question a fundamental assumption about adaptive systems.

2.4 Simulations of Nonlinear Dynamical Models

G. Mayer-Kress

SFI Member Gottfried Mayer-Kress (Beckman Institute, U. Illinois) and his collaborators worked on a variety of projects involving simulations of nonlinear dynamical systems with varied applications to international relations.

2.4.1 Global Information Systems and Regional Crisis as Problems of Complex Adaptive Systems

With A. Hubler and D. Pines

Unsustainable developments on any level of organization will eventually lead to increased stress and crises. What we are currently witnessing is the impact of resetting the development of countries that were previously under the influence of the Soviet Union or other authoritarian governments. With support from NATO Grant 920921, these researchers have studied new possibilities and options that modern computer and communication technology offer for regional crisis management. In combination with the use of the theory of complex adaptive systems, they explored new approaches to the modelling of regional conflict and how new fundamental strategies for international organizations like the United Nations or NATO could be developed. The theoretical model of Hubler and Pines (SFI External Faculty members, both of U. Illinois) can serve as an example of the issues of anticipation and control that play a central role for those problems. Part of their results were presented at the 1992 Santa Fe Institute Complex System Summer School and at a NATO-SHAPE symposium.

2.4.2 Integrated Global Models

With R. Costanza (U. Maryland) and B. Hannon (NCSA)

Global sustainable development depends on many different subsystems that can be of global, regional or even local scale. Among the most recognized subsystems are climate, ocean, economic, ecological, and socio-political subsystems. The challenge is to integrate those subsystems into a global, integrated models that allows an efficient access to global data and information systems and also the exchange of information between the different models. It has been widely recognized that single global models, like those studied mainly in the '70s (Forrester, Club of Rome), will not be flexible and adaptive enough to adequately model a complex evolving world. Mayer-Kress and his collaborators are working on distributed, integrated models. The paradigm that seems to be appropriate to describe the new type of global, integrated models is that of a Global Brain, which exhibits many analogies to the development and workings of biological brains . The integration of some of the current models was presented at the conference "Computing in Social Sciences 1993," to be held May 19–21,1993.

2.4.3 Sustainable Agriculture
With A. Hubler and W. Fulkerson

Deere & Co, one of the largest manufacturers of agricultural equipment and a member of the SFI Business Network for Complex Systems Research, is interested in sponsoring research on the application of nonlinear methods of complex, adaptive systems to explore mega-trends in agriculture, specifically developments in the direction of a sustainable agriculture. Progress in satellite-based global-positioning capabilities make site-specific ("foot-by-foot") farming feasible. The next generation of combine harvesting machines will be able to play the role of information and data stations, tightly integrated into global agricultural and atmospheric modeling: Data on soil, pest, and crop properties at a given location can be stored and used as input for simulation models that will serve both as input for agricultural planning as well as for global environmental change simulations.

In a joint SFI/CCSR project, Mayer-Kress, A. Hubler (U. Illinois), and W. Fulkerson (Deere) are exploring the integration of existing agricultural models and databases in a global network of information and simulation systems that study the impact of global change on sustainable development. Specifically they are working on extensions of the IMAGE/ESCAPE models of the Climate Research Unit, Norvich, UK; National Institute for Public Health and Environmental Protection , Bilthoven, NL; and the Environmental Change Unit, Oxford, UK. These apparently state-of-the-art models, although limited and incomplete, could serve as a good starting point and as a frame work.

The Integrated Model to Assess the Greenhouse Effect (IMAGE) is a policy-oriented model based upon scientific principles. More specifically, it is a parameterized simulation model, developed for the calculation of historical and future emissions of greenhouse gasses on global temperature and sea level rise and ecological and socio-economic interests in specific regions. The greenhouse problem is modelled as a dynamical system that evolves in time as a nonstationary Markov chain, with discrete time steps of a half-year and a simulation time of 200 years, from 1900 to 2100. The year 1900 was chosen to represent the end of the pre-industrial era. The system is modular in design. Each module is a sequence of first-order differential equations and ordinary algebraic equations solved using the Runga-Kutta methods. The linkage between modules is represented by using the output of one module as the input to the next. The resulting model is deterministic.

2.4.4 Global Simulation and Information Systems

The evolution of natural life can be viewed as going through stages of increasing complexity: From the evolution of matter in the Big Bang to molecular, cellular, biological, and cultural evolution, we see transitions to new organizational forms, once the lower-level system has reached a "minimal complexity." In the work by Terry Spencer this threshold was measured as the number of tightly interacting units. The value of 10^{10} seems to occur repeatedly. If we look at the number of human brains on this planet, we realize that we are rapidly approaching this number. With the advent of global high-speed communication, fast computers, and nonlinear theory of complex adaptive systems, some realization of a "global brain" might become feasible. Mayer-Kress and his collaborators are experimenting with, and have demonstrated, a very rudimentary attempt at such an early linked network of distributed information and simulation systems. The elements of this network can be any object anywhere on the global network: It can be the access to a database, to a simulation server, to animated results of a simulation , or to an artificial life simulator of a local ecology or global system.

The basic platform consists of a NeXT Cube with NeXT-Dimension graphics/video extensions and high-level voice control.

2.4.5 Probe Project: Installation of an Integrated Computer Lab and Interface for the Computing in Social Sciences, a meeting held May 19–21,1993

One of the biggest challenges in the Grand Challenges in Social Sciences will be the interdisciplinary integration of a large diversity of computational tools in social science and how to interface them with simulations and models from natural sciences. Models are often presented with only informal descriptions and the computational implementation. This makes it rather difficult and time-consuming to use a network of models covering different areas. We would need to develop interactive tools for conceptual presentation of the structure of the models. Mayer-Kress and his collaborators envision that this will be done in some hyper-media format. In the"EarthStation" project, mentioned below, they mainly used hyper-media diagrams on NeXT computers.

In the context of databases and information systems, a lot of progress has been made in recent years in creating standard formats and conversion software—significant contributions came from NCSA. These collaborators proposed to implement those standards in the models used by the participants at the Probe Project meeting and to link the participant's systems together into one coherent network. Thus they installed an integrated computer lab for the meeting to explore the state of the art in:

- globally distributed simulation systems,
- geographical and wide area information systems, and
- high-speed communication systems.

The idea was that participants either would contribute access to their software/data systems ahead of the actual conference and/or the relevant software would be ported to one of the NCSA supercomputers. In the conference lab those systems were provided with a common format and interface. During the conference the integrated system was introduced and made available for participants to exploit for possible future collaborative projects. The collaborators expect that the software will undergo mutations during this experiment and new structures and qualities will emerge.

The guiding principle could be the paradigm of a "Global Brain" where each user is not flooded by terabits of information, but, as soon as a specific question needs to be answered, this can be done in real time through text, image, video, sound, virtual reality, simulation, and direct communication. Forerunners of this concept have been presented successfully in the collaborators' "EarthStation" installation on the Ars Electronica 1991 festival in Linz/Austria. They believe similar efforts are underway, for example, in Germany. They would like to create links to those centers and make them available to the conference participants.

They expect that this on-site computer network lab will be the seed for network-based collaborations. Specifically they are convinced that this concept of loosely connected interactive data/information/simulation networks will evolve into distributed global simulation systems which will replace or incorporate traditional large world models.

2.5 Rendering and Display: Audification
G. Kramer

In October 1992, SFI sponsored ICAD '92, the First International Conference on Auditory Display. The program was chaired by SFI Member Gregory Kramer. Thirty-six researchers met at the Santa Fe Institute to discuss the use of non-speech audio at the human/machine interface. The participants represented institutions from Europe, Scandinavia, the United States, and Canada. Their disciplines included computer science, cognitive and experimental psychology, computer music, electrical engineering, mathematics, human factors, and complex systems.

Over three days, two key research areas were discussed:

1. auditory interfaces, or the use of sound to enhance user interfaces, and

2. auditory data representation (including sonification). This includes (a) the use of sound to monitor and comprehend data by using the data to control a sound synthesizer, and (b) audification, or the direct translation of time-sequenced data into sound (including shifting the time scale of the data to shift it into the audible domain).

These areas are not distinct disciplines, but rather points along a continuum. This continuum runs from presenting fixed-state information (auditory interfaces) to presenting continuous quantitative information (sonification). For example, auditory interfaces that display quantitative information were demonstrated (e.g., not only is someone accessing a specific hard drive, but how much file manipulation is occurring). Within the area of auditory data representation, there was a sub-continuum that was contingent upon the nature of intermediary structures between the data and the human listener. Audification is the direct playback of data samples, with only time shifting to get the playback rate into the audible domain, while sonification employs intermediary structures, such as sound synthesizers, which are controlled by the data to produce the auditory display. The hardware tools and software structures that advance one research area could clearly benefit other research areas. Discussions of these tools provided fresh approaches, as well as new insights, into the underlying theories of how to use sound to convey information. Also providing common ground were issues of auditory perception, such as the formation of auditory gestalts, auditory streaming, semiotics, timbre perception, and the impact and techniques of spatialization. Applications discussed included: comprehending complex, high-dimensional systems; telepresence and virtual reality interfaces for the vision impaired; geophysical data; financial data analysis; census data analysis; chemistry data for blind users; software debugging; sonar parallel computation analysis; user interfaces for vision-impaired persons; monitoring background processes; and medical instrumentation.

Over the course of the workshop numerous relationships emerged which appear to be leading towards research collaborations. General discussions of issues in the field will be continued on the ICAD e-mail list established at the Santa Fe Institute. Some collaborations between individuals follow.

- Tecumseh Fitch (Brown U.) and Chris Hayward (SMU) are looking into running experiments to determine whether subjects can discern the difference between earthquakes and nuclear tests by the use of audification.

- Stuart Smith (U. Massachusetts) and Carla Scaletti (U. Illinois) are working on synthesis algorithms that together would be optimal for sonification.

- Sheila Williams (Sheffield U.) and Gregory Kramer (SFI) are developing an experiment to test the effects of learning on users of sonification systems.

- Meera Blattner (Lawrence Livermore) has invited Jonathan Cohen (Apple Computer), David Wessel (UC Berkeley), Chris Hayward (SMU), and Robin Bargar (NCSA), all of ICAD, to speak at a lecture series at Lawrence Livermore National Laboratory.

- Tara Madyastha (U. Illinois) and Roger Powell (Silicon Graphics) are sharing concepts related to the underlying code for manipulation of audio in computer systems and networks.

- James Ballas (Naval Research Lab) and Gregory Kramer (SFI) are developing a project on the use of synthetic sound to deliver information. They are also beginning collaboration on a CD/book on novel instances of sound that conveys information.

- James Ballas is also establishing relationships with Bill Gaver (RANK Xerox, EuroPARC) and Jonathan Cohen on informational sound projects.

- David Lunney (East Carolina U.) is proposing a project with Tecumseh Fitch (Brown U.) on testing auditory displays for chemical analysis instrumentation.

- Beth Wenzel (NASA Ames) has been discussing work with Chris Hayward (SMU) and Meg Withgott (Interval Research); Kevin McCabe (NASA Ames) is looking into working with Beth Wenzel (NASA Ames) on shared technology. They had not been intimately familiar with each other's work prior to ICAD.

Three group efforts aim to establish a modicum of platform compatibility between different researchers. The first is a direct outgrowth of the fact that there were more demos on the SGI Indigo computer than on any other platform. SGI is interested in establishing their computers as a standard auditory display research tool. To this end, a network of sonification researchers, all using SGI computers, may come into being.

Secondly, following up on a suggestion by Roger Powell of SGI, Kramer has contacted the synthesizer manufacturer Kurzweil/Young Chang about using their K2000 at a number of sites. For researchers obliged to use the MIDI control protocol, whether because of portability or the availability of commercial software and hardware, the K2000 could be a useful tool if perhaps six research sites would begin to use it and would exchange configurations and applications.

A third initiative under way is the establishment of a standard sonification system data format. It was agreed that another ICAD should be held, probably in two years. This may be another conference in Santa Fe if the community agrees that this is the best way to go and the Institute agrees to support the conference. Other venues discussed include the Association of Computing Machinery (ACM) and IEEE.

Finally, the proceedings volume is an important step in defining the research area of auditory display. It will be the first time that an entire book has been dedicated to the field.

2.6 Integrative Activities

2.6.1 Common Principles of Complex Systems

One of the Institute's most important 1992 working group meetings was a ten-day workshop in July on Common Principles of Complex Systems. The group reviewed work done at SFI and elsewhere over the past dozen years, compared approaches and results, then began to construct an overview of the commonalities in the behavior of complex systems.

During the meeting more than two dozen members of the SFI family presented papers on a wide variety of topics illustrating various levels in the hierarchy of complexity. Subjects ranged from cellular automata, which share some of the properties of complex systems; through the origin of life and of proteins; the functioning of RNA and viruses; developmental complexity and evolution, including the evolution of individuality and of the mammalian brain; ecological systems; cognition and human learning; concluding with the social sciences, particularly economics but also touching on a broader set of questions dealing with global sustainability and human behavior.

Participants talked about mathematical and computational methods for describing the behavior of complex systems—more or less approximately. These tools include neural nets, genetic algorithms, nonlinear dynamical methods for dealing with chaos, and the notion of self-organized criticality leading to "avalanches" at all scales.

This material will be available in *Integrative Themes*,the proceedings volume for this meeting due from SFI/Addison-Wesley by year-end.

2.6.2 The Second Metamorphosis of Science
E. A. Jackson

While on sabbatical leave from University of Illinois, E. Atlee Jackson conducted research to determine the changes that have occurred to the foundations of science during the past century. These changes are presently not recognized by most scientists, and yet will have a profound influence on the program of science in the future. By "a program of science" is meant the way in which the studies of diverse phenomena in nature (in physics, chemistry, biology, economics, and some societal phenomena) are related to each other. No research, such as that going on at SFI or in Jackson's group at the Center for Complex Systems Research at the University of Illinois, can become a coherent program without first establishing the foundations of the scientific methods being used.

This foundation explored by Jackson consists of two parts: (1) the operational methods that are used to obtain information about phenomena in nature, and (2) the limitations (and potentials) of these operational methods, and how they relate and complement one another. The first metamorphosis of science occurred over the period 1570–1790, during which the importance of physical experiments was established and differential equations as mathematical models of nature were introduced. These two operational methods, coupled with many mathematical developments in this new area, and new physical phenomena to be modeled by this method, led to many unwarranted assumptions about the generality of this approach in understanding natural phenomena. Therefore, the foundation, particularly part (2), was never clarified, but this caused only limited difficulties in the progress of science. Beginning in 1890 a series of limitations of mathematical modeling were established (proved mathematically), all of which established that science cannot achieve the program that has been proclaimed by many (e.g., Einstein, Weinberg, Hawking, etc.)—namely, the program of reduction and synthesis, by which we would ultimately arrive at a "theory of the universe." These results were generally ignored, until the operational methods were increased around 1950 by the development of the digital computer, and the subsequent new method of computer experiments. This finally catalyzed the completion of the second metamorphosis of science, in which two entirely new foundational parts, (1) and (2), have been established.

This new foundation of science has removed the reduction/synthesis program of the past, with its associated attempts to obtain theories "capable of accounting for everything," and challenges us to now find the new thread that will hold a scientific program together.

3. PATTERNS IN INFORMATION AND COMPLEXITY

Complex Systems present themselves in a variety of modes including many different temporal time series, computational systems such as cellular automata and Boolean nets, stochastic processes, dynamical systems, and so on. Several studies are under way at SFI that seek to discover characteristics of the underlying processes and to predict their future behavior by examining the data series, the information content according to various measures, the emergent hierarchies or topologies, and the intrinsic computational limits to complexity.

3.1 Patterns in Chaotic Data in the Nervous System

J. Theiler

Through a grant from the National Institute of Mental Health James Theiler and his colleagues—D. Chialvo, Syracuse U.; Doyne Farmer, Prediction Company; Brant Hinrichs, U. Illinois; and A. Longtin, McGill U.—are investigating allegations that the electroencephalogram (EEG) is chaotic and, in general, are exploring the use of nonlinear time series methods in the characterization of the dynamical behavior of the nervous system.

Neurons are highly nonlinear. It remains unclear, however, exactly what role nonlinearity plays in their information-processing capabilities, and how this is expressed in the behavior of systems of neurons.

Chaos theory offers a new possibility for explaining apparently random behavior in the nervous system. It has been suggested as the underlying cause of randomness in several different neural systems. However, in most cases the evidence for chaos remains inconclusive, in large part because the data analysis is based on techniques that are notoriously unreliable, such as currently popular algorithms for computing fractal dimension.

On the other hand, there are many mathematical models of the nervous system where chaos occurs. Since these are well-defined mathematical models, it is possible to analyze them and determine unambiguously the existence and properties of any underlying chaos. In neuroscience, however, there is a large gap between theoretical models and the real nervous system; there are assumptions and unknown parameters in the models that leaves their relevance to real neurophysical phenomena uncertain.

One such system is the electroencephalogram (EEG), which has become a widely used tool for the monitoring of electrical brain activity, and whose potential for diagnosis is still being explored. Over the last decade, there have been many published claims that various EEG time series exhibit evidence of low-dimensional chaos. If true, the implications are striking. However, the interpretation of this evidence has been controversial. One problem is that the algorithms for characterizing chaotic time series were originally developed in the context of large, relatively noise-free data sets, whereas EEG time series are often short and noisy. The algorithms in principle can distinguish chaos from noise, but in practice they often fail.

While low-dimensional chaos may be exhibited in free-running oscillations, a more common situation in neuroscience is for a response to depend on a stimulus. Theiler and his colleagues have developed methods for analyzing the possible nonlinear dependence of the response to the stimulus. The method distinguishes between chaotic and nonchaotic responses. They have recently acquired a considerable data base of evoked response EEG time series and intend to apply these methods to determine if there is a nonlinear relationship. The ultimate purpose is to discover any underlying deterministic structure that may currently lie hidden in apparently random neural phenomena.

3.1.1 Electroencephalography (EEG) and Magnetoencephalography (MEG)
With D. Chialvo, B. Hinrichs, and A. Longtin

EEG and MEG signals represent the summed activity of large numbers of neurons and are of considerable interest because they can be noninvasively recorded in normal human subjects and in patients with neurological or psychiatric disorders. Although they are closely related, EEG and MEG reflect different aspects of current flow within the brain and have different sensitivities to current sources of different orientation and distance from the recording sites. Because of these differences, the group is conducting separate analyses of EEG and MEG data to determine whether their differential sensitivity to different current sources is associated with different dynamical characteristics. They are also conducting analyses on combined EEG and MEG data obtained under identical conditions since there is evidence that the two types of activity are complementary in important respects. Spontaneous activity will be analyzed using time series methods, while activity associated with sensory, motor, or cognitive events (so-called event-related potentials, ERPs, and event-related fields, ERFs) will be analyzed in terms of nonlinear input-output maps.

3.1.2 Spontaneous Activity in Deep Sleep and Other Normal States
With D. Chialvo, B. Hinrichs, and A. Longtin

Analysis of fractal dimension suggests that deep sleep EEG signals for humans can be characterized as low-dimensional chaos. However, given the problems and limitations of fractal dimension computations, this is still inconclusive. Theiler and his group are re-examining this question using the same data sets that have already been analyzed in terms of fractal dimension, to determine whether their methods lead us to the same conclusions. Some of these have already been supplied to the group by Paul Rapp. In addition, in collaboration with C. C. Wood of the Biophysics Group at Los Alamos, they intend to examine independently recorded data sets using single- and multi-channel EEG and MEG. Is there predictability beyond that of linear time series models? Does it satisfy tests for low-dimensional chaos? How do these characterizations change for different states of consciousness? Are the properties of EEG and MEG significantly different? How do properties vary with location and between individuals?

3.1.3 Epileptic Seizures
With D. Chialvo, B. Hinrichs, and A. Longtin

Another important question to be addressed in spontaneous recordings is possible changes in dynamical properties of EEG signals in epileptic seizures. In collaboration with C. C. Wood (LANL), T. R. Darcey of Yale University School of Medicine, and John Milton of University of Chicago, the group is assessing the dynamical properties of EEG signals recorded from the scalp and from implanted electrodes in patients undergoing evaluation for possible neurosurgery as part of the Yale Epilepsy Surgery Program and the University of Chicago Epilepsy Surgery Program. Dynamical properties of scalp and intracranial EEG will be assessed before, during the initiation and spread of, and after focal seizures of medial temporal lobe origin. These results will be compared to those of Darcey and Williamson using more conventional time-series analyses.

3.1.4 Event-Related EEG and MEG Signals
With D. Chialvo, T. Darcey, B. Hinrichs, A. Longtin, G. Mayer-Kress, J. Milton, G. Mpitsos, M. Palus, R. Siegel, and C. Wood

Theiler's group's analyses of event-related EEG and MEG signals focuses on stimulus-response mappings and classification. Specifically, they are comparing the dynamical properties of one-second segments of data immediately preceding and following unpredictable stimuli in order to characterize more accurately the relationship between spontaneous and stimulus-related activity. Does a stimulus elicit new activity with properties that are different from those of spontaneous activity? Or, does it produce a reorganization of the spontaneous activity itself? They are also using nonlinear mappings in an effort to improve classification of single- and multi-channel EEG and MEG activity obtained under different stimulus conditions. Such improved classification tools may ultimately prove valuable in discriminating normal from abnormal brain activity associated with clinical neurological disorders.

A central element for success in the analysis of neural data is close collaboration with experimentalists. Toward this end the group has established collaborations with several experimental neuroscientists, including Terry Darcey, John Milton, George Mpitsos, Ralph Siegel, and Chris Wood.

In principle, the techniques described here can be applied to a wide variety of different kinds of data. Since much of the analysis simply assumes the data come from a "black box," in principle one does not have to know very much about the black box in order to apply them. However, in practice, these methods have many "meta-parameters," such as the sampling time used to construct the state space, its dimension, the order of the local models, and the neighborhood size. One of the goals is to automate the search for good metaparameters as much as possible, so that it can be done with a minimum of human intervention. However, for the moment there is no substitute for insight about the problem, and this is best done through close collaboration between someone who understands the methodology and someone who understands the experiment that produced the data.

Another critical reason for involving experts is to know *what* data to analyze. Experimentalists often have very clear intuitive ideas about where to search for simple behavior. Searching for underlying (nonlinear) simplicity is precisely what the project's methods are designed to do but, in order to do this, it is critical to know where to look.

In a related project, Gottfried Mayer-Kress (Beckman Institute, U. Illinois) and Milan Palus (Prague Psychiatric Center) are working on nonlinear methods of EEG analysis. Their approach is the integration of spatial, but also temporal transforms of the EEG signal into wavelets. This method has proven to be highly superior to Fourier analysis methods in areas of self-organized coherent structures in fluid turbulence. The geometrical and dynamical properties of EEG or MEG activity is sufficiently similar to those data, so that they expect a large improvement of the accuracy of this analysis method compared to previous spectral approaches. This holds not only for spontaneous electromagnetic brain activity but also—and especially—for evoked responses, where the signal is intrinsically localized in space and time. Palus is working on the methodology of nonlinear analysis of EEG data. Progress in this area is essential for the repeatability, interpretation, and possible clinical application of these algorithms.

3.2 Wavelet Analysis of Complex Spatio-Temporal Data

G. Mayer-Kress and U. Parlitz

Mayer-Kress and Ulrich Parlitz (U. Darmstadt, Germany) are developing methods for the efficient reconstruction of low-dimensional attractors from spatio-temporal chaos data with localized structures. Focusing on the numerical analysis of several examples of spatio-temporal chaotic data from simulations and experiments, they compare different algorithms of discrete and continuous wavelet decompositions with respect to their performance in reconstruction essential coherent structures of the data. Specifically, they present dynamical reconstructions with respect to the scales and locations of evolving structures. They can demonstrate that these methods not only accurately reproduce the dynamics of these structures, but that they can also be used for very specific filtering of isotropic and anisotropic structures. They are comparing the temporal reconstruction of dynamical models from the wavelet decomposed data with that from Karhunen-Loeve decomposition.

3.3 Comparative Time Series Analysis
N. Gershenfeld and A. Weigend

A wide range of new techniques are now being applied to the time-series analysis problems of predicting the future behavior of a system and deducing properties of the system that produced the time series. New techniques, such as the use of connectionist models for forecasting and time-delay embedding to estimate complexity, promise to provide insights unavailable through more traditional statistical and econometric time-series techniques. Unfortunately, the realization of this promise has been hampered by the difficulty of making rigorous comparisons between competing techniques within a discipline and by the difficulty of making comparisons across discipline boundaries.

In 1991 SFI researchers Neil Gershenfeld (Harvard) and Andreas Weigend (Xerox Palo Alto Research Center) ran a time-series prediction and analysis competition through the Santa Fe Institute to help clarify the conflicting claims. A small set of interesting experimental data that spans a wide range of attributes of interest (such as low- versus high-dimensional, deterministic versus stochastic, continuous versus discrete, scalar versus vector, etc.) was made publicly available over computer networks, and then quantitative analyses were accepted in the areas of (1) forecasting (using the data to predict a segment of the data set that was not made publicly available), (2) numerical measurement (estimating such quantities as the number of degrees of freedom of the underlying system or the information production rate), and (3) system identification (inferring a model of the governing equations from the time series).

A May 1992 meeting studied the results of the competition. It offered a unique opportunity to advance the understanding of time-series analysis in a wide range of disciplines, because participants had analyzed identical data sets, and quantitative evaluations of the relative performance of their techniques were available. The thrust of the workshop, then, consisted of a common effort to understand the overall results, rather than isolated presentations by investigators claiming research advances. If some techniques prove to perform much better than others, it will clearly be important to understand why this is so; if the performance differences on a class of problems are small, it will be equally important to understand why the theoretical distinctions break down in practice. The workshop participants were drawn from the entrants in the competition. One day of the workshop was spent on each section of the competition, and the competition time-series data were made available on workstations during the workshop so that new ideas can be implemented as they arose. The proceedings of the meeting will be published as part of SFI Studies in the Sciences of Complexity series.

3.4 Physics of Information
E. A. Jackson and G. Mahler

Gunter Mahler's (U. Stuttgart) 1992 work at SFI focused on the interplay between quantum physics and information. Variants of the question "Does the tree fall when nobody looks?" gain a new, though often confusing, meaning in the realm of quantum mechanics. It appears that in so-called closed systems nothing "really happens." Mathematically the dynamics can be described as a kind of eternal rotation of a state vector in its respective high-dimensional state space. This behavior is fundamental to what some call "endophysics." The "exophysical" approach calls for external observers, which thus requires a separation of the quantum world into the "relevant system" and an environment. As a result, the dynamics of the relevant system is no longer universal and no longer deterministic but rather stochastic and depends on details of the environment (boundary conditions, driving fields, etc.), i.e., on the interface to the outside. Information now enters on various levels: specifications of the environment, pre-knowledge about the observed system (scenario), and the flow of information from the system into the environment in terms of registered "events" (e.g., in terms of "clicks" of a photodetector).

Pertinent problems that Mahler is considering follow. (1) What do we know about reconstruction from pre-knowledge about the scenario and the observed events? Can we predict the behavior, can we classify, can we simulate? (2) To what extent can one control the observed system—despite the inherent stochasticity—by choosing an appropriate environment? This would amount to exploiting the "adaptive" nature of quantum objects. (3) How does the "environment" become an environment? It is as quantum mechanical as the observed quantum object. This problem relates to the notorious quantum measurement problem.

Part of E. Atlee Jackson's (U. Illinois) SFI research in 1992 concerned how living systems can acclimate to changes in their environment. What he thought would be a rather easy dynamic problem turned out to have some very interesting aspects. The problem centers around how a system monitors its "health," which requires a self-referential action. Jackson refers to this type of "internal examination" dynamics as Endodynamics—it differs fundamentally from externally applied control dynamics, in which the goals are externally set. To acclimate, the system must sense the environment, keep a short-time memory of the condition of its "health," seeking to optimize it (a genetically set condition). A simple model that incorporated all of these actions was developed. The role of acclimation in the evolutionary adaptation process appears to be a large, basic, unexplored area of dynamics. Jackson anticipate developing a more sophisticated model.

4. ADAPTIVE COMPUTATION

A major focus of research at SFI is on "adaptive systems"—systems that adapt their behavior over time in response to what has been encountered previously. Many of the complex systems being studied at SFI exhibit adaptation to some extent. Research efforts on computation concentrate on either building computational models of adaptive systems or on using novel computational methods inspired by natural adaptive systems for solving practical problems. Genetic algorithms, neural networks, classifier systems, and simulated annealing are examples of such methods. The techniques have been used both as models of natural phenomena and as novel methods for solving practical problems; as a result of their dissimilarity to traditional methods, they had led to a broadening of notions of how information processing takes place.

The Adaptive Computation program at SFI serves as a formal structure for integrating research in this field at the Institute. The purpose is to make fundamental progress on issue in computer science that are related to complex adaptive systems.

In March 1992, a founding workshop reviewed the status of this research with the aim of defining major areas of further inquiry. The workshop consisted of eleven invited talks and a number of shorter presentations on various "Visions of Adaptive Computation." Invited talks were: Neural Networks, Richard Palmer; Adaptive Computation in ECHO, John Holland; Computational Learning Theory, Nick Littlestone; Adaptive Behavior of the Immune System, Alan Perelson; Evolution and Ecology of Digital Organism, Thomas Ray; Temporal Difference Learning, Richard Sutton; Simulated Evolution and Punctuated Equilibria, W. Daniel Hillis; Foundations of Genetic Algorithms, Melanie Mitchell; Adaptive Computation in Robots, Nils Nilsson; Symbolic Machine Learning, Thomas Dietterich; and Quantification of Evolutionary Adaptation, Norman Packard.

In May Melanie Mitchell (U. Michigan) began a 2.5-year residency as director of the program. In 1992, work proceeded on a number of projects.

4.1 Applications of Adaptive Computation Techniques

4.1.1 Protein-Folding Prediction
J. Bryngelson and A. Lapedes

Alan Lapedes (LANL) and Joe Bryngelson (LANL) are using novel adaptive computation techniques for data analysis to address one of the most important unsolved problems of molecular biology and biophysics: the prediction of three-dimensional protein structure from amino acid sequences.

A protein is made up of a linear sequence of amino acids, but it is the protein's three-dimensional structure that primarily determines its function. This three-dimensional structure (i.e., how the protein "folds up" in space) is determined by the linear sequence of amino acids, but it is not currently known precisely how a given sequence leads to a given structure. A successful prediction method would not only be a tremendous advance in our understanding of the biochemical mechanisms of proteins, but, since such an algorithm could conceivably be used to design proteins to carry out specific functions, it would have a profound, far-reaching effect on biotechnology and the treatment of disease.

The existing massive amount of data on amino acid sequences surpasses unaided human capacity for analysis, and completely overwhelms any current techniques of protein structure determination, such as x-ray crystallography, which is very time-consuming and difficult. A main hope for making progress is the development of automatic methods of data analysis and prediction. There have been a number of attempts to address the protein-structure problem using standard neural network techniques and other machine-learning methods, but the results have been disappointing—the best algorithms to date have less than a 65% prediction accuracy rate, whereas much greater accuracy is needed for any real applications.

Lapedes and Bryngelson's approach is based on the belief that progress will most likely occur when the computational aspects are studied with, and related to, the physical, chemical, and biological aspects of the problem, and they propose three related projects, each employing novel adaptive computation methods. In brief, these are: (1) using an adaptive algorithm to learn appropriate parameter values for a potential energy equation that predicts secondary (intermediate) protein structure; (2) using a coevolutionary scheme involving neural networks or classifier systems to discover new secondary-structure classes that yield better predictions than the commonly used classes of alpha-helix, beta-sheet, and coil; and (3) applying a bootstrapping technique similar to "decision-directed learning" that can hopefully greatly increase the amount of useful protein structure data without having to use costly methods such as x-ray crystallography.

In addition to Lapedes' and Bryngelson's research on applying neural networks to predict protein structure, Lapedes is collaborating with Melanie Mitchell (SFI), Rick Riolo (U. Michigan), and Geoffrey Hinton and Evan Steeg (both of U. Toronto) to apply genetic algorithms to various aspects of protein structure prediction. One approach is to use the GA to perform a type of unsupervised conceptual clustering in order to discover useful new protein secondary-structure classes. Another approach is to apply GAs to the "inverse folding" problem—to search the space of possible amino acid sequences to find those that are likely to give rise to a given desired structure. Success on these projects would produce a powerful new computational tool for protein structure prediction, which is at present one of molecular biology's most important open problems.

4.1.2 Operations Research and Complex Adaptive Systems Models
J. Holland and S. Pollack

During a May 1992 workshop, participants compared and contrasted Operations Research (OR) models with SFI's work on complex adaptive systems (CAS). The meeting was co-chaired by SFI External

Professor John Holland (U. Michigan) and Steven Pollack (U. Michigan). Topics included an exploration of the commonalities and differences between the operations research and complex adaptive systems approach with emphasis on the use of computer models to perform "gedanken" experiments in CAS as compared to the (putative) emphasis on construct validity of OR models; measuring the "goodness" or "quality" of mathematical models of complex phenomena; measuring the performance of optimization heuristics and algorithms for truly large-scale (and possibly non-stationary) situations; and discussing these points with reference to specific research interests such as combinatorial optimization or n-armed bandit problems.

4.1.3 Approaches to Artificial Intelligence
N. Nilsson and D. Rumelhart

The field of artificial intelligence (AI) has as its goal the development of machines that can perceive, reason, communicate, and act in complex environments much like humans can, or possibly even better than humans can. Even though the field has produced some practically useful machines with rudiments of these abilities, it is generally conceded that the ultimate goal is still distant. That being so, there is much discussion and argument about what are the best approaches for AI. Best in the sense of laying the core foundations for achieving ultimate goals as well as best in the sense of producing practically useful shorter-term results. Thus, a number of different paradigms have emerged over the past thirty-five years or so. In order to acquaint researchers and others with these paradigms and their principal results, the Santa Fe Institute held workshop in October to which advocates actively working in the different approaches were invited. The workshop was chaired by Nils Nilsson and David Rumelhart (both of Stanford U.). The four major approaches that were considered were (1) symbol-processing approaches, (2) biocomputational approaches, (3) heterogeneous approaches, and (4) integrative approaches. Topics covered included (within section one) declarative knowledge bases and logical reasoning, SOAR, a production-rule style architecture, state space searching, and "blackboards," an approach in which a central data structure is manipulated by knowledge source programs. Biocomputational approaches included connectionist AI, "situated" artificial creatures, artificial evolution, and discussion of real-time learning and control. Heterogeneous approaches covered distributed artificial intelligence, economics-based methods, massive-parallelism, and agent-oriented programming. Integrative approaches included discussion of integrated robots and integrated agents.

4.1.4 Computation, Dynamical Systems, and Learning
J. Crutchfield, J. Hanson, M. Mitchell, J. Pollack, and S. Omohundro

In November 1992 the Adaptive Computation program sponsored a working group meeting on "Computation, Dynamical Systems, and Learning." The group considered these questions among others: What is the relationship between the computational ability of a system and its dynamical behavior? In particular, does the ability for nontrivial computation require a system to be "near the transition to chaos"? What exactly does this mean? What is the relationship between the computational ability of a system and its complexity, as defined in various ways? How can these quantities best be measured? How does evolution, operating on physical systems, navigate in computational or complexity space? How is evolution able to increase the computational ability of a system? What is the relation between the ability of a system to learn or adapt and its computational capabilities? What is the relation between learning and adaptation, and a system's dynamical properties? Speakers and topics were Evolving Cellular Automata to Perform Computational Tasks, Melanie Mitchell; Innovation, Induction, and Complexity, James P. Crutchfield (UC Berkeley); Chaotic Pattern Bases for Cellular Automata, Jim Hanson (UC Berkeley); Cognition as a Complex System, Jordan Pollack, (Ohio State) and Learning and Recognition by Model Merging, Stephen M. Omohundro (International Computer Science Institute).

4.2 Modeling Adaptive Systems

4.2.1 The ECHO Model
J. Holland, S. Forrest, T. Jones, and J. Brown

John Holland's ECHO model is a simulated ecology: it consists of populations of evolving, reproducing agents distributed over a geography with different inputs of renewable resources at various sites. Each agent has simple capabilities—offense, defense, trading, and mate selection—defined by a set of "chromosomes" that evolve via a genetic algorithm. Although these capabilities are simple and simply defined, interacting collections of agents can exhibit analogs of a diverse range of phenomena, including ecological phenomena (e.g., mimicry and biological arms races), immune system responses (e.g., interactions conditioned on identification), evolution of "metazoans" (e.g., emergent hierarchical organization), and economic phenomena (e.g., trading complexes and the evolution of "money"). Thus, although the system is couched in terms of the language of biological ecologies, it is meant to be general enough to model phenomena in a number of areas. This generality can help shed light on commonalities among phenomena in these diverse areas and can get at the essence of some central questions about complex adaptive systems.

Terry Jones, a Ph.D. student from Indiana University, began a two-year residency at SFI working closely with Stephanie Forrest and John Holland to develop a UNIX version of Holland's ECHO model. Jones' dissertation also concerns ECHO.

One of the first real applications and verifications of the validity of ECHO will be done in conjunction with James Brown (U. New Mexico). Brown has wide experience and approximately 25 years of data from ecologies that are perturbed by the removal of species. ECHO is particularly well-suited for simulations of this kind. Jones is already reporting ECHO runs that exhibit characteristics of natural ecosystems.

4.2.2 Swarm Simulation System
C. Langton

Chris Langton (LANL and SFI) is developing the "Swarm" Simulation System—a generalized programming framework for simulating and studying the complex behaviors that arise in systems composed of many components. This work is described in Section 5.2.

4.2.3 Natural Evolution of Machine Codes: Digital Organisms
T. Ray and D. Pirone

Thomas Ray (U. Delaware) and graduate student Dan Pirone (U. Washington) were in residence at SFI for several months working on evolving efficient parallel machine codes. Tom Ray, a tropical ecologist, has developed a computer model of an ecology of evolving self-replicating organisms living in an environment with limited resources. In his model (called "Tierra"), the organisms are self-replicating computer programs that are subject to mutations, the environment is the memory of the computer, and the limited resources are memory space (RAM) and CPU time. The model was started off with a single "ancestor" self-replicating program that was placed in memory and allowed to run. The results of this initial experiment were quite startling: not only did novel replicating algorithms evolve, but rich ecological communities appeared immediately. Evolution generated a succession of ecological forms, as the "creatures" living in the RAM discovered that other creatures were the most significant feature of the environment. Thus evolution generated methods of exploiting other creatures, and of defending against exploitation, in an evidently autocatalytic process of diversification with no clear end in sight.

In addition to the surprising ecological diversity of the system, Ray found that running the system under conditions that favor small efficient algorithms has produced remarkable optimizations of machine code. This has turned out to have significant unexpected implications for the design of computer architectures and software. The surprising power of simulated evolution to produce novel and extremely efficient machine code programs has led Ray to formulate ideas about how this power can be harnessed for the practical goal of evolving efficient machine codes to perform specific tasks.

At SFI from February through August, 1992, Ray extended this work through two interrelated projects: (1) improving the system as a model of biological evolution and (2) applying the results of the system to the practical problem of evolving efficient machine code programs to perform specific tasks, particularly in the context of massive parallelism. Graduate Fellow Dan Pirone worked with him on this research. In order to improve the system as a biological model, Ray worked on incorporating computational analogs of organized sexuality, multi-cellularity, and intercellular communication into the existing system. These are all biological mechanisms that allow biological organisms to become increasingly complex. (This is closely related to Holland's work on the evolution of "metazoans.") These mechanisms make the biological model richer, and at the same time they enhance the evolvability of machine code, and the complexity of programs that can be evolved. It is precisely these biologically richer forms of digital organisms that are most likely to provide a method of generating software capable of fully exploiting the power of massively parallel computers.

4.2.4 Using Artificial Adaptive Agents to Model the Formation of Economic Markets
J. Miller

John Miller (Carnegie-Mellon) is developing a computer model to study the formation of economic markets. How such markets are formed and evolve is a central issue in economics, both from a theoretical and practical standpoint: for example, understanding what policies should be enacted to allow for the formation of the most effective market institutions is an issue of great importance in developing countries and countries attempting to implement free-market economies.

Miller's model is similar to Holland's ECHO system in that it involves a set of economic agents whose trading strategies evolve under a genetic algorithm. Initial work on this model has yielded a number of interesting results on how a set of self-interested, profit-maximizing agents, each with limited knowledge, can evolve trading and bidding strategies consistent with an efficient allocation of resources for the entire population—a striking example of the evolution of cooperation in an economic context. In Miller's original model, individual agents evolved strategies in response to a fixed market institution (i.e., a fixed set of rules for bidding competitions). Miller proposes extending this model to allow for a more realistic coevolution between agents and market institutions. Not only will the agents evolve new strategies, but the market institutions will evolve as well, making the discovery of new types of markets possible.

Such simulations should lead to a variety of insights. Can such a system effectively and efficiently distribute and use system resources, as economic theory would predict? Do we see a variety of institutional forms developing in this world? A goal is to learn, via these computer simulations, what types of market institutions would be most effective in a given real-world situation. As a long-term goal, in addition to applications in economics, this artificial economy could also provide new adaptive-computation techniques for accomplishing a variety of important tasks related to resource allocation. Adaptive artificial economic systems could be used to automatically regulate the activities of, say, a large-scale computer network, a complex production process, or a production learning system.

4.2.5 A Population Genetic Model

Aviv Bergman

As first shown by Muller in 1916, crossover events do not occur independently of one another within regions of about 40 map units or less. In general, the occurrence of a crossover event reduces the chance of another crossover event nearby. As a result, the frequency of a double crossover event among three closely linked genes deviates from the product of those of two single crossover events within the region. The deviation from this product is called interference.

It has often been suggested that interference results from the physical interaction of the chiasmata. Chromatids must bend to form chiasmata, and it may be physically too difficult to bend enough to permit two chiasmata near one another. Although this effect should be fairly local, interference is known to occur between genes more than 30 map units apart.

Furthermore, negative interference has been documented, where the frequency of double crossover event is greater than expected. These observations suggest that physical constraint is not the full story behind interference. It is therefore of interest to determine how interference would evolve if it were under genetic control. Because interference affects the average rate of recombination, we might expect that interference would evolve similarly to modifier genes that control the rate of recombination directly. Studies on the evolution of recombination have demonstrated a "reduction principle" for the evolution of the recombination rate between two loci subject to constant viability selection. Beginning from an equilibrium at which the loci under selection are in linkage disequilibrium, a selectively neutral modifier locus will evolve to reduce the recombination rate at the selected loci.

In 1987, Altenberg and Feldman showed that the reduction principle holds for an arbitrary number of viability loci tightly linked to any modifier that produces "linear variation" of the transmission process. By linear variation Altenberg and Feldman mean that a single parameter controls the probability that each gametic type is transformed to a new type in a specific, simple manner. A modifier of recombination between two loci produces linear variation in transmission, but a modifier of recombination among many loci will only produce linear variation under the assumption that only a single break per chromosome is allowed, that is, under complete interference. The existing analytical work, therefore, does not allow us to infer how a modifier of interference will evolve based solely upon its influence on the recombination rate.

In this work we numerically analyze a four-locus model designed to investigate the evolution of interference among three loci subject to different types of viability selection. We will see that, in the cases of multiplicative overdominance and mutation-selection balance, modifiers of interference evolve as would be predicted based upon their effect on the average recombination rate. That is, under multiplicative overdominance, modifiers of interference introduced near one of the high-complementarity equilibria evolve to reduce the recombination rate, while modifiers introduced near a mutation-selection balance equilibrium may evolve to increase the recombination rate whenever the rate of decline in fitness with the number of deleterious alleles is faster than multiplicative, as was found for modifiers that act directly on recombination.

The evolution of learning capabilities in organisms is one of the more perplexing issues in evolutionary biology. Several studies on the evolution of learning have proposed mechanisms to explain this phenomenon. The objective of this research program is to increase our knowledge in this area as it pertains to natural as well as artificial organisms, by analytical and numerical studies of the dynamics of population under different environmental conditions. This research is long-term and will bring together knowledge from population genetics, dynamical systems theory, and information theory, and it will be guided by relevant biological evidence.

Several studies on the evolution of learning have proposed the idea of learning as a mechanism to adapt to changes in the environment during an individual's lifetime. These studies are based on the "absolute fixity argument." That is, in the presence of an absolutely fixed environment an individual should develop a genetically fixed pattern of behavior (assuming some cost is associated with learning).

On the other hand, in an absolutely unpredictable environment, where the past and present states of the environment bear no information about the future, there is nothing to learn and, assuming some cost to learning, there is no driving force for learning capabilities to evolve.

In 1991 Stephens proposed a different approach that takes into account the individual's life history. Stephens argues that the pattern of predictability in relation to an individual's life history determines the evolution of learning. His study concludes that the value of learning is in dealing with environmental events that change between generations and are regular within generations.

An alternative approach is to view learning as the ability of an individual to construct a correct model of its environment and, by proper use of the model, to be able to predict future states of its environment. The population genetic model described here addresses this environmental modeling question.

A population genetic model for the evolution of learning will serve as the basis of this research. Some preliminary analytical and numerical results will also be presented. Bergman is interested in the conditions under which learning will evolve in a population of individuals initially lacking learning capability. To answer this question in a population genetic framework, the following must be defined: a genotype, a mapping from a genotype to a phenotype, and a (time-dependent) fitness function.

In addressing the question of the evolution of learning, one should state first what it is that an individual should learn from its environment. In its simplest form an environment can, at time t, take the value s_t with $s_t \in \{0;1\}$. Each environmental state has a viability value, E_{s_t}, associated with it. Here Bergman considers the following viability values: E_0 for $s_t = 0$ and E_1 for $s_t = 1$.

One way to create a changing environment is to generate a state sequence where the state is the outcome of a stochastic process. This means that the s_t are realizations of random variables S_t. Consider a changing environment where the state is the outcome of an independent (biased) stationary stochastic process; namely, there exists a probability $P(1) = \Pr(s_t = 1)$ that the environment will be 1 at time t, and

$$P(0) = \Pr(s_t = 0) = 1 - \Pr(s_t = 1) = 1 - P(1)$$

that it will be 0. For simplicity let $P(1) = P$ and $P(0) = 1 - P(1) = 1 - P$.

Other ways of creating a stochastic environment will also be considered; for example, in a changing environment where the state, $s_t \in \{0;1\}$, is a stationary first-order Markov process, the state of the environment at $t + 1$ depends only on the state at time t. That is, the conditional probability $\Pr(S_{t+1} = s_{t+1} \mid s_t, s_{t-1}, \ldots, s_0)$ depends only on s_t for all t.

Learning will be viewed as the process by which an individual models its environment to predict its state in the future. For example, the outcome of learning will be the discovery of the set of conditional probabilities $\Pr(s_{t+1} \mid s_t)$. Thus, individuals that can predict the environmental state will (probably) have higher average fitness than individuals with inferior prediction capabilities.

Generalization to higher-order Markov processes is a straightforward extension of this analysis.

4.3 Theoretical Foundations

4.3.1 Foundations of Genetic Algorithms
S. Forrest and M. Mitchell

The development and application of adaptive algorithms cannot make true progress without the concurrent development of a theoretical understanding of these algorithms. Essential theoretical questions concerning these algorithms include the following: On what general types of problems is a given algorithm likely to succeed, and why? Can predictions be made about the expected performance of a given algorithm on a given problem? To what degree does the representation of the problem affect the performance of the algorithm? Stephanie Forrest (U. New Mexico and SFI) and Melanie Mitchell (U. Michigan and SFI) are investigating the foundations of adaptive algorithms, with special emphasis on obtaining results that will be useful to the other projects in which these algorithms are applied.

Genetic algorithms (GAs) have been rising in popularity recently as simple but surprisingly effective search-and-optimization techniques on a variety of problems. GAs are also now being used in a number of models of complex systems in various disciplines (e.g., Holland's ECHO model and Miller's Adaptive Agents model, described above). Though the algorithm is simple to state and program, its behavior is often complex and, in spite of its popularity and widespread use, there is still little understanding of precisely how the algorithm works, and little knowledge of what characterizes the class of problems on which it is expected to perform well. Making progress on these issues is of central importance to the field of adaptive computation: understanding the GA better is both of intrinsic interest and also necessary in order to give some guide as to when and how it should be used in solving problems and in making models.

Forrest and Mitchell are conducting an in-depth study of GAs, with the goal of answering three fundamental questions: (1) What makes a problem easy or hard for a GA—that is, how can we characterize the problems on the GA works well and those on which it does not? (2) To what extent does the GA scale well—that is, to what extent will the GA continue to perform well as the complexity of the problem increases? And, (3) what does it mean for a GA to perform well—that is, what are appropriate ways of measuring the algorithm's performance?

They are addressing these questions by studying in detail the GA's performance on a set of hand-constructed "fitness landscapes" containing various configurations of features that are particularly relevant to the GA. A longer-term goal is to develop a set of statistical measures that will characterize a given landscape in terms of these features, and thus allow the prediction of some aspects of the GA's likely performance on it.

Initial simulation work on this project yielded some surprising and counterintuitive results about the way the GA processes "building blocks" (or schemas). Forrest and Mitchell are extending this work to gain a better understanding of the causes of these results, and to apply similar simulations to more complex landscapes. The long-term goal is a a complete understanding of how building blocks are processed in the genetic algorithm. The final result of these investigations will be a much deeper understanding of how genetic algorithms work and what they are good for, and thus will contribute to all areas of adaptive computation in which these algorithms are used.

4.3.2 Foundations of Supervised Learning Methods
D. Wolpert

SFI Postdoctoral Fellow David Wolpert is exploring the general theoretical foundations of supervised learning systems, or systems that learn from examples. Such systems are at present the most widely investigated and most widely used learning methods in the machine-learning community: some of the better-known examples are various neural network systems, classification algorithms such as ID3, and some forms of Holland's classifier systems. There are already a number of formal approaches to supervised learning, but as yet these formalisms have had quite limited practical value for researchers designing and applying new learning methods. On the other hand, there are many practical heuristics that are well known in the supervised learning community, but as yet such heuristics have no rigorous theoretical foundation.

Wolpert's work focuses on the construction of a rigorous and useful theoretical framework for supervised learning systems. Such a framework is essential to the study of adaptive computation for three reasons: first, as a tool to aid one's understanding of learning systems as a whole; second, to complement computer simulations as a means of predicting the behavior of particular learning systems in particular environments; and, third, as a possible means of improving the adaptive strategies employed by such systems.

This framework will be used to address a number of issues for supervised learning systems. It can help us understand the mathematical conditions under which a particular learning system will best be able to generalize. It also can be of direct real-world applicability, for example, in constructing tests for phenomena such as "over-training"—a serious potential problem for all supervised learning systems. Finally, it can address certain issues in "meta-learning": the problem of automatically learning best how to learn. Wolpert has recently developed a meta-learning system "stacked generalization" that learns best how to combine information from several other learning systems. If successful, this work will have significant implications for how to improve the performance of all types of supervised learning systems.

In August 1992, a workshop "The Future of Supervised Machine Learning" was jointly sponsored by SFI and LANL. Topics included unifying the formalism used in supervised learning; advantages and limitations of Bayesian inference; generalization error and the bias-variance trade-off, CV and GCV; and solfing large-scale multi-class learning problems using error-correcting output codes.

4.4 1993 Activities

Work continues on the projects mentioned above. In addition, working group meetings are taking place on these topics: adaptive computation in robotics; adaptive computation and economics; sparse distributed memory; genetic algorithms and real genetics; and modeling the interaction among evolution, learning, and culture.

5. ARTIFICIAL LIFE/SWARM

Closely related to the Institute's work in adaptive computation and theoretical biology is its research in artificial life which simulates lifelike processes in the form of adaptive computer programs. Artificial life is synthetic biology. It involves attempts to put together life, evolution, and other biological phenomena from first principles for the purpose of scientific experiment and engineering applications. As such, artificial life is not restricted to the medium of carbon-chain chemistry in its attempts to synthesize biological phenomena. Rather, it uses whatever medium is most appropriate and convenient for the synthesis of the phenomenon under study. Because of their extreme behavioral plasticity, computers are often the medium of choice.

5.1 Third Artificial Life Symposium

C. Langton

In mid-June 1992 more than three hundred participants attended the third Artificial Life symposium, a five-day meeting chaired by SFI External Assistant Professor Christopher Langton. The event was co-sponsored with the Center for Nonlinear Studies at Los Alamos National Laboratory.

The first four days of the conference consisted of talks on the synthesis of lifelike phenomena in wetware, software, and hardware, in that order. The fifth day was devoted to an "Artificial 4-H Show" including a Lego-Logo design competition, Robot Olympics, a micro-mouse contest, plus talent shows and other events for hardware and software organisms. Evenings consisted of poster sessions, special interest group meetings, a video-night, and a night at "The Alife Cafe," an evening of general discussion and philosophical debate.

Invited speakers included Rodney Brooks (MIT); Leo Buss (Yale); Jean-Louis Deneubourg (Brussels); Gerald Joyce (Scripps Clinic); John Koza (Stanford); Hans Moravec (Carnegie-Mellon); P. Prusinkiewicz (Regina); Tom Ray (SFI and U. Delaware); Julius Rebek (MIT); and Luc Steels (Brussels).

Artificial Life III, the proceedings volume from this meeting, will become a part of the SFI series in the sciences of complexity. Also anticipated is a video proceedings from the conference, a compilation of computer experiments and simulations.

5.2 The Swarm/Process Gas Simulation Project

D. Hiebeler and C. Langton

Many of the scientists at the Santa Fe Institute and elsewhere studying complex systems and emergent phenomena find it necessary to construct computer simulations for specific systems as diverse as social insect behaviors, chemical networks, economic models, and so on. These simulations at some level share a basic kind of computational framework; the result is that individual scientists are constantly reinventing and rewriting this framework in which to implement the specifics of their model. The goal of this project is to provide (within the context of these kinds of studies) a general-purpose simulation environment, within which it will be much easier to construct these simulations.

The Swarm system allows one to conduct simulations consisting of large numbers of interacting "objects" or agents. The user should be able to write a few modules to describe a few different types of objects, plug them in to the general system, and run the model. For example, a biologist modeling mosquito populations could write a module to describe the mosquito's behaviors that she is interested in, as well as a module to describe the relevant features of the environment, and be ready to run. Or an economist could write a module to describe the behavior of an economic agent, and another to describe the properties of the market. If a rich toolkit is also supplied as part of the package, perhaps the scientist won't even need to write a module from scratch; she can either put together existing modules and tune their parameters for her own purpose, or else start out with a module from the toolkit and modify it.

Swarm will supply a general user interface that the users may easily customize for their specific objects; there will also be a library of analysis modules available. They also hope that the user would be able to run on a workstation or a parallel computer, with little or no modification to their code. Constructing a complex-systems simulation and interacting with it should not be a complex (or painful) process.

As mentioned above. Swarm is essentially a system for controlling a number of computational objects interacting with each other. Each object has a few standard attributes managed by the system, as well as whatever private data are needed. Routines are provided that allow the user to register new objects with the system, at which time the system attributes are filled in, and to deregister objects that one wishes to destroy.

SFI's development of the Swarm system is fundamentally modular. It entails both developing general-purpose modules that will be called by special-purpose experiments and the development of special experimental subsystems. Effort on the project has so far been divided between developing general-purpose modules and work on simple examples of special-purpose experiments. There is a natural interplay between these efforts. The development of the special experimental modules has greatly illuminated the characteristics needed for the general-purpose modules. The experiments that have been developed to date have been chosen not for their intrinsic interest or possible practical applications but as sample problems that will aid in the further development of the tools.

So far, the following three experiments have been implemented in the Swarm system.

5.2.1 "HeatBugs" Generic Experiment

The Heatbugs experiment is not a simulation of any actual physical system; it is simply a typical, generic experiment that embodies many of the basic characteristics that are exhibited by the systems that they hope to study with Swarm. This system consists of independent but identical agents ("heatbugs") that are free to move independently of each other in a two-dimensional region. Each agent emits "heat" at a continuous rate, and the "heat" diffuses uniformly from the point of emission. The agents each seek a location, by following the local "heat" gradient, such that the location optimizes at an (adjustable) intermediate value the local value of the "heat" variable. This simple dynamical system, though easily described, is not amenable to analytical solution and is a useful laboratory for exploring the needed characteristics of the Swarm system.

The developed modules that are specific to this experiment are:

hbug	describes the bugs for the HeatBugs experiment and
heatspace	describes the Space (which diffuses heat) for HeatBugs experiment.

5.2.2 Traffic Flow on a One-Dimensional, One-Lane Road

The independent agents (cars) in this system are constrained to move in one dimension, to maintain a minimum separation, so that they do not to collide, and to change their speeds according to some adjustable parameters of the system. The experiment allows one to explore the parameter ranges in which "traffic jams" occur, either spontaneously or from external influences, and the dynamical stability of these structures.

The modules developed that are specific to this system are:

trafcar	describes the cars in the Traffic experiment and
trafroad	describes the road in the Traffic experiment.

5.2.3 Ant-Foraging Behavior

In this experiment the independent agents (ants) are constrained to move independently in a limited two-dimensional region near their "nest," engaged in the search for "food" which they attempt to bring back to the nest. Ants lay "pheromone" trails between their nest and some food sources. The "pheromone" diffuses from the source and decays temporally. (This experiment was originally done by

Mitch Resnick under his *Logo system. It has some obvious features in common with "heatbugs" but also introduces some new features.)

The modules developed that are specific to this system are:

logoants	describes the ants in the Ant-foraging experiment and
fheatspace	describes the Space for the Ant-foraging experiment, which handles diffusion of pheromones as well as keeping track of the locations of the nest and food.

All three of these experiment modules are now complete and operating.

Fundamental to the design of the Swarm simulation system is that a variety of supplemental modules are being developed that are not specific to any subsystem but are general enough to be used in a standard way by a variety of special applications. The following supplemental modules have been developed that are used by all of the experiments:

ximage	displays two-dimensional color images under the X11 windowing system;
xprobe	displays "probe" windows so that one can track objects in the system; and
mspace	"space-manager" which keeps track of the locations of items. This is used by ximage and xprobe; it allows the user to click the mouse on an object in order to bring up a probe-window displaying the characteristics of that object.

Implementing the above experiments has forced us to rethink and reorganize the Swarm system on many occasions. They believe they are coming closer to having the basic design established and, in the future, fewer changes to the basic system should be required.

There remains a long list of additional system development tasks planned for the coming months. Some (but not all) of the major changes that still need to be done are:

- The organization of the "space" modules needs to be seriously rethought. This is the biggest issue on their to-do list, and also one of the more difficult. They need a way to separate the definition of "space" from the variables that are defined across the space and the dynamics of those variables; but they need to do it in a way which will not be too inefficient.

- Add formal "children" to each object, so the tree can be traversed in either direction.

- Add "start-run-mode" and "stop-run-mode" routines to module objects, since, on some hardware platforms, special hardware routines may need to be invoked when the user starts/stops running. It could also be useful for other things, e.g., setting up displays.

- Add some support routines to do useful things on the object tree, e.g., search for objects of certain types in subtrees.

- Perhaps make experiment files much more complex, almost like a module, so that they can send messages to objects, etc. Or else think about a nice way to write a module whose only task is to load and call other modules.

- There are some issues to work out regarding sending messages containing certain types of data, which will need to be resolved before the system can be implemented on a parallel computer.

- Decide how to implement a way to let objects be "meeting places" for other objects. This will allow us to have objects "stick together" and behave as one object, among other things. Probably they need all the parent/child support routines to be in place before trying this.

- Think of a good way to use the new "step-data" that gets passed to step-functions. There may be some automatic ways to use this to allow a mechanism of inheritance, but it will take a lot of thinking to decide how to go about doing it.

- Find a way to specify order dependency of step-functions. For example, it may be desirable to tell the system "run the ximage module's step-function after all other modules' step-functions."

- The method for initializing parameters in a module needs to be made much nicer; right now you have to go through all the parameters one at a time. Instead, a window displaying all of them at the same time should pop up, so if you don't want to change any, you don't have to slowly go through them all.

- Write a "graph" module to display some data over time.

- When you probe an object, it should be displayed in a different color in the ximage window, so that you can tell which object(s) you are probing.

- Make the ximage module dump images in a standard format such as TIFF (right now it just dumps the image in raw format, or Sun format which is not standard).

- Do a simple economic-agent model. This will open up a new class of problems, since they want the same agents to run in a spatial or a non-spatial way. They are holding off on this until they take care of several of the other issues, since doing this model will probably double the size of their to-do list.

- Allow some kind of templates for the xprobe windows, so you could display the data in different ways (e.g. as sliders, dials/knobs, etc.) as well as displaying things just as simple labels.

5.3 A Lattice Model of Polymer Dynamics
S. Rasmussen and J. Smith

Undergrad intern Joshua Smith spent three months during summer 1992 developing a lattice model of polymer dynamics, with Steen Rasmussen. The original motivation was to develop a tool for understanding the formation of membranes, and their role in the emergence of complexity; however, the first step, creating lattice polymers, proved challenging enough.

This lattice polymer system may prove useful for studying (real) polymers, colloidal suspensions, and other systems in which "extended objects" interact with a gas of point-like objects. And with certain extensions, it should be possible to model the formation of membranes.

The approach might be described as Alife-like, in that they have tried to capture the underlying logic of polymer motion, with less emphasis on the physical particulars that implement the informational process. For example, if one tugs on the first atom in a polymer, the next atom in the chain will not (cannot) start moving until it has, in effect, received some sort of message from the first. Normally these messages are called forces, but it may be profitable to think of them in the context of information theory. In formulating the model, they concentrated on which information must be transferred, and when, in order to coordinate the motion of the individual atoms that make up the polymer; they did not concern themselves with how the information is actually encoded in the photons sent back and forth by real atoms. The only major "natural" constraint imposed on the communication protocols is that nonlocal communication of information are not allowed.

In the model, forces (messages?) are transmitted by particles. Presently, there are three forces. The weakest (the "kickon" force) is meant to model the jostling of the polymer atoms by water molecules; it may eventually be replaced by an explicit representation of the water molecules. The strongest is the "bond" force, which tends to pull an atom toward the two particles it is bonded to. A particle interacts through this force only with the two others it is bonded to. By saying that this force is strongest, they mean that if a kickon "suggested" that the end particle move so far to the right that it separated from the chain, the bond force would override this suggestion, and the bond would not break. The intermediate strength force is one that repels any particles that are *not* bonded together. This has the effect of causing the polymer to tend to straighten, and prevents collisions between unbonded particles. This force is crucial because, without it, there is no possibility of communication (interaction) between particles that are not bonded together. Absurd might be a better term than unrealistic for a system that only allowed bonded particles to interact with one another, as they quickly discovered when the added kickons caused their polymer to curl up and interact with itself. The repellon force makes it quite straightforward to model the interaction of several polymers—in fact, since the rules are entirely local, there is no distinction between the interaction of a curled polymer with itself and the interaction of two separate particles.

6. MODELS OF GENOMIC STRUCTURE AND ORGANIZATION, GENE INTERACTION, AND GENOME EVOLUTION

6.1 Covariation of Mutations in the V3 Loop of HIV-1: An Information Theoretic Analysis

Robert M. Farber, Bette T. M. Korber, Alan S. Lapedes, and David H. Wolpert

The V3 loop of the Human Immunodeficiency Virus Type-1 (HIV-1) envelope protein is a highly variable region that is both functionally and immunologically important. This group has used an information theoretic quantity called mutual information, a measure of covariation, to quantify dependence between mutations in the loop using available amino acid sequences from the V3 region. Certain pairs of sites, including noncontiguous sites along the sequence, do not have independent mutations, but display considerable, statistically significant, co-varying mutations as measured by mutual information. For the pairs of sites with the highest mutual information, specific amino acids were identified that were highly predictive of amino acids in the linked site. The observed interdependence between variable sites may have implications for structural or functional relationships; separate experimental evidence indicates functional linkage between some of the pairs of sites with high mutual information. Further specific mutational studies of the V3 loop's role in determining viral phenotype are suggested by their analyses. Also, the implications of their results may be important to consider for V3 peptide vaccine design. The methods used are generally applicable to the study of variable proteins. A manuscript is in press.

6.2 Protein-Folding Prediction Using Novel Applications of Neural Networks and Genetic Algorithms

Melanie Mitchell, Rob Farber, Alan Lapedes, Rick Riolo, and Evan Steeg

These collaborators are in the early stages of investigating some novel methods of applying neural networks and genetic algorithms to the prediction of a protein's structure from its amino acid sequence. There have been a number of machine-learning approaches to this problem, but none so far has been successful enough to achieve what biologists really want: to design new proteins that perform desired functions. One approach they are taking is to use genetic algorithms and neural networks to perform a type of unsupervised conceptual clustering in order to discover useful new protein secondary-structure classes. Another approach is to apply GAs to the "inverse folding" problem—to find amino acid sequences that are likely to give rise to a given structure. Success on these projects would produce a powerful new computational tool for protein-structure prediction, which is at present one of molecular biology's most important open problems.

6.3 DNA Sequence Data and Pediatric AIDS
Bette Korber

Bette Korber from the Theoretical Biology and Biophysics Group at Los Alamos National Lab has joined the SFI research staff on a half-time basis to work on Project ARIEL, a program supported by the Pediatric AIDS Foundation and the Magic Johnson Foundation. Project ARIEL brings together the expertise of several of the top AIDS laboratories in the country to explore many aspects of mother-infant transmission of HIV-1, the virus that causes AIDS.

Not all pregnant HIV-1 infected women transmit the virus to their offspring; epidemiological studies indicate that there is a transmission rate of 15–30%. Many elements of this transmission are still a mystery. Why does transmission occur in some, but not all, women? When transmission occurs, is it predominantly happening early during pregnancy, across the placenta, or is it happening during birth? Does the mother's immune system play a role in preventing transmission? Do viruses that are transmitted to babies have common characteristics? Understanding the answers to these questions may give insight into methods that could help reduce the risk of transmission.

What is unique about Project ARIEL is that several laboratories will work together, using the same mother-infant blood samples. Different tests will be conducted in different laboratories, each with different expertise (immunology, viral biology, viral sequencing, etc.). The effectiveness of the mother's immune response against the virus obtained from her own blood samples, as well as virus isolated from her baby, will be assessed. The viral load in the mothers will be estimated, and the biological properties of the viral isolates will be characterized. Because HIV-1 is highly variable—it varies even within a person—the evolution of the virus in the mothers will be studied throughout gestation and also will be followed in infected infants after birth.

All of this data—along with patient profiles describing the health status of mother-infant pairs—is being brought together by Korber who is looking for meaningful patterns in the DNA sequence data, and correlations between the different kinds of data sets.

6.4 RNA Secondary Structure
Walter Fontana, Peter Schuster, and Peter Stadler

These collaborators are concerned with the simplest genotype-phenotype relation that is realized in nature: RNA. Complementary base pairing provides a replication mechanism by templating and, at the same time, causes a single-stranded RNA to fold back on itself into a structure. They view the folding of polynucleotide sequences as a map that assigns to each sequence a minimum free-energy pattern of base pairings, known as secondary structure (hereafter referred to as "shape"). Considering only the free energy leads to an energy landscape over the sequence space. Taking into account structure generates a less visualizable nonscalar "landscape," where a sequence space is mapped into a space of discrete shapes. The shape affects replication and degradation rates, recognition processes involving proteins, and catalytic activity. The evolutionary dynamics of viral and structural RNA, therefore, depends highly on the properties of the map that assigns a structure to each sequence.

Fontana, Schuster, and Stadler have worked extensively on a statistical characterization of RNA secondary structure, on the correlation properties of the landscapes mentioned above, on the distributions of energy and structure distances with respect to distance in sequence space, and on the reverse folding problem. Their main results to date show that:

1. RNA folding is characterized by very short structure correlation lengths compared to the diameter of the sequence space.

2. The energy, as well as the structure autocorrelation function, is characterized to a reasonable approximation by one length scale.

3. The characteristic length of the energy and of the structure landscape scale linearly with sequence length.

4. The characteristic length for structures strongly depends on the nucleotide alphabet.

5. Binary sequences, AU or GC, have very short correlation lengths, indicating that they are very likely to change their structure with few changes in the underlying sequences.

6. GCXK sequences, with XK denoting two artificial nucleotides with the same pairing strength as GC, are less sensitive to changes than binary sequences.

7. Natural AUGC sequences are even less sensitive than GCXK.

8. They have checked the influence of the non-Watson-Crick pair. Disabling GU pairs in AUGC sequences strongly influenced the energy autocorrelation (shorter correlation length), but had no or little effect on the structure autocorrelation. They conclude that the sensitivity difference between AUGC and GCXK is due to the unequal base stacking and pairing energies associated with GC and AU pairs.

9. ABCDEF sequences (GC pairing strength) have a very low sensitivity.

This suggests that a natural four-letter GCAU alphabet is a good compromise between (a) enough structural variety to support biological function and (b) sufficient, but not excessive, stability towards changes in the sequence.

They have recently discovered that:

1. The frequency distribution of shapes at different scales of resolution follows a generalized Zipf law.

2. Almost all frequent shapes are found within a small neighborhood of any random sequence ("shape space covering").

3. The entire space of sequences can be traversed in steps consisting of one or two mutations without ever changing the shape of an average start sequence ("neutral networks").

Connections with data have been made. This work evidently bears on the emerging technology of applied molecular evolution.

Simple statistical model landscapes, like Kauffman's NK model, are often used as a proxy for understanding realistic landscapes, like those induced by RNA folding. We made a detailed numerical and analytical comparison between the energy landscapes derived from RNA folding and those obtained from the NK model. The comparison leads to an estimate for $k = 7$ to 8, independent of n, where n is the chain length. While the scaling behaviors agree, the NK model does not agree with their RNA data in regard to the fine structure of the landscape. The reason seems to be the extremely high frequency of neutral neighbors: that is, neighbors with identical energy (or structure), in the RNA case. The physical process of polynucleotide folding—as far as it is properly abstracted by the a thermodynamic algorithm—is not in the class defined by the NK model. The neutrality issue has profound effects on the number and the distribution of local optima as well as biased walks on both landscapes. These are the features in which the disagreement is most apparent. At the same time these are also the features that are the most relevant to evolutionary optimization.

6.5 Theory and Application to a Random Heteropolymer Model of Protein Folding
J. D. Bryngelson

The theoretical prediction of the structure of a molecule or an assembly of molecules, such as a cluster, frequently involves the minimization of a potential function. Examples of this activity range from using sophisticated techniques of modern quantum chemistry to obtain predictions, with high accuracy, of structures of small molecules in the gas phase, to using semi-empirical potentials of mean force to predict the structures of macromolecules in solution. Particularly for large molecules, much effort has gone into developing accurate potentials that require tractable amounts of computer time for their evaluation, and into developing efficient algorithms for finding the deepest minimum of these potentials. Bryngelson has addressed another aspect of structure prediction: the accuracy required of a potential that predicts molecular structure. If the potential function is not accurate enough, then the best minimization algorithm possible is still useless for predicting structure. However, if the accuracy requirements are known, then definite goals for potential creation exist, and researchers can concentrate on problems that are solvable with the present potentials. One of the most important unsolved problems in molecular structure prediction is the prediction of protein structure from amino acid sequence. Therefore, Bryngelson applied a general formalism that he developed for accuracy requirement calculations to simple protein model to estimate the accuracy needed for a potential that predicts protein structure.

More specifically, he considered the problem of predicting the full three-dimensional or tertiary structure of a protein. Most attempts to predict protein tertiary structure are, at least implicitly based on the thermodynamic hypothesis, which states that a protein in solution folds to the configuration that minimizes the free energy of the protein plus solvent system. Typically the solvent is water. This hypothesis suggests a general strategy for predicting protein tertiary structure from sequence. First, one develops a semi-empirical potential function which approximates the free energy of the protein-solvent system as a function of the three-dimensional configuration of the protein. Next, one attempts to solve the problem by finding the configuration that minimizes the approximate potential function. This configuration is the predicted protein structure.

Although the above general strategy has successfully predicted the structure of small polypeptides, it has met with limited to non-existent success in predicting the structure of globular proteins. This failure has typically been attributed to the difficulty of finding the the minimum of the potential functions, so that a great deal of effort has gone into algorithms for optimizing these potential functions. Bryngelson's work analyzes a complementary question, the potential accuracy question: How accurate must the potential function be so that configuration that minimizes it is, indeed, the correct structure? The major result of this investigation is that the probability of predicting the correct structure is given by

$$\text{probability} = 1 - k(N^{1/2}\eta/B) \qquad (1)$$

where B is the scale of the monomer-monomer interaction energies, η is the scale of the inaccuracy of the these interaction energies, N is the number of monomers, and k is a constant of order one. Equation 1 implies that, if a potential function is to predict the correct structure, the monomer-monomer interaction energies must have proportional error of less than $1/N^{1/2}$. For a globular protein, N will typically be between 50 and 400, so the required accuracy in monomer-monomer interactions is about 5–15%. It is important to note that this result is the accuracy required for getting all of the monomer-monomer contacts right, that is, predicting the entire contact map with perfect accuracy, a stringent requirement for a potential function. Proteins with 60+% of correct contacts are usually considered to be structurally homologous.

Therefore, the protein calculation should be extended to calculate the probability of predicting a structure with a specified fraction of correct contacts. This extension will require that the formalism and the model be improved. The formalism must be extended so that it can be used to calculate the probability of predicting one of many, rather than just one, low energy state. The model can be extended in two ways. First, the statistical mechanics of the model potential function could be solved in an approximation that is more accurate than mean field theory used to derive Eq. (1). Some progress has already been made in this direction. Second, the model potential function could be extended by incorporating new effects that are alleged to be important in protein folding, such as the principle of minimal frustration.

6.6 Computer Approaches to Macromolecular Structure Prediction and Spin Glass Physics

P. Stolorz

SFI Postdoctoral Fellow Paul Stolorz has been working on computer approaches to macromolecular structure prediction and spin glass physics. Biological macromolecules share several distinctive features, with heterogeneous physical systems such as spin glasses (e.g., the presence of quenched disorder), and these are suspected of contributing very strongly to their structural and folding characteristics. However, little progress has been made at analyzing in a precise way models incorporating these features. In particular, analytical approaches are notoriously difficult. Stolorz has adopted an approach to these questions that relies heavily upon computing power, in order to study various disordered systems that cannot easily be investigated by analytic means. At SFI his projects focus on:

6.6.1 Prediction of Heteropolymer Structure from First Principles

A set of novel enumeration procedures has been developed, based upon a recursive transfer matrix approach, which are able to describe the low-energy states of lattice heteropolymer models. This allows the low-temperature regime of these models to be very carefully explored, calculations that have not until now been possible. The methods share much in common with several other topics, including the study of self-avoiding walks, and related models of homopolymers. The general approach is considered of sufficient promise that plenary presentations have been solicited describing it at several international conferences, including the 1993 meeting of the American Physical Society in Washington, DC.

6.6.2 Low-Temperature Properties of Spin Glasses

Using essentially the same methods, Stolorz has been able to measure the Parisi order-parameter function for spin glasses in three dimensions, together with the susceptibility, at zero temperature on small lattices, with no equilibration problems at all. Several other illuminating calculations are also possible, and currently underway. They include the extension of this computation to larger lattices on the Connection Machine (this should help resolve the controversial issue of the nature of the low-temperature phase), contour plots of constant susceptibility in the temperature/external field plane, and extensions to other spin glass models, including Potts glasses. There is, of course, a remaining source of error, namely that due to the finite-size effects. Stolorz is developing methods to address this issue as well. The idea now is to use the exact enumeration procedure referred to above as a heuristic within a larger Monte Carlo procedure. In particular, he plans to merge the method with another successful Monte Carlo heuristic that has been developed in the context of ferromagnetic models, namely "cluster decompositions." The use of cluster decompositions in a spin glass setting is in its infancy, but a combination of clusters with exact enumeration shows great promise as a powerful Monte Carlo approach for these models.

6.6.3 Prediction of Side-Chain Packing in Globular Proteins

The technique is being applied also to predict the energetically favorable side-chain configurations in globular proteins. A well-known and important subproblem of the protein-folding problem, this technique is the subject of considerable research within the pharmaceutical industry. The method shows promise of being able to compute the optimal side-chain configurations for protein sequences of realistic size containing at least 50 amino acids. In contrast, current state-of-the-art methods are unable to deal with peptides of more than about seven amino acids.

6.6.4 Elucidation of the Low-Temperature Properties of RNA-Folding Methods

With W. Fontana and P. Schuster

The basic method also can be used to investigate the low-energy configurations of RNA secondary structures. This ability represents an advance over previous approaches, as it enables one to compute observables of interest at a series of arbitrary temperatures, without requiring that the entire calculation be redone each time. Computations along these lines are currently being developed in collaboration with Walter Fontana (SFI) and Peter Schuster (Institut für Molekulare Biotechnologie and SFI).

6.6.5 Inverse Protein Folding

The goal of this work is to begin with a well-defined protein structure,and to determine the amino acid sequence or (sequences) with which it is compatible. One might hope to use such an approach eventually in the context of rational drug design. Prof. Jeff Skolnick (Scripps Clinic) has developed an "inverse" potential function which appears to be particularly promising. Stolorz is using this function as the starting point for inverse-folding investigations, using both stochastic and exact enumeration methods to search the sequence space.

7. COMPLEXITY, LEARNING, AND MEMORY IN THE IMMUNE SYSTEM

Within the Theoretical Immunology Program a number of different research problems were studied in 1992. These include the application of genetic algorithms to problems in the immune system; modeling somatic mutation of antibodies during the course of an immune response; modeling immune networks using novel computer simulation techniques to determine whether they are capable of generating immune responses; and modeling immune responses to tumors.

7.1 The Application of Genetic Algorithms to Problems in the Immune System

S. Forrest, R. Hightower, and A. Perelson

Maintaining diversity of individuals within a population is necessary for the long-term success of any evolutionary system. Genetic diversity helps a population adapt quickly to changes in the environment, and it allows the population to continue searching for productive niches, thus avoiding becoming trapped at local optima. In genetic algorithms (GAs), it is difficult to maintain diversity because the algorithm assigns exponentially increasing numbers of trials to the observed best parts of the search space (cf. Schema Theorem; due to John Holland). As a result, the standard GA has strong convergence properties. For optimization problems, convergence can be an advantage but, for other problems, it can be detrimental. Further, even in optimization, strong convergence can be problematic if it prematurely restricts the search space.

Forrest, Hightower, and Perelson also have been using the genetic algorithm to understand the evolution of antibody and T cell receptor (TCR) variable (V) region genes. In order to make a large diverse repertoire of antibodies and TCRs, the immune system utilizes a number of different gene segments. Thus a variable region heavy chain is composed of V, D, and J gene segments, each segment chosen randomly from a library of many segments. When segments are joined together, errors are made introducing additional variability. This combinatorial mechanism for generating diversity can potentially produce many more V regions than are found in an animal at any one time. This then raises the question of how evolution acts on the gene segment libraries. A particular molecule that provides protection may or may not be made in any animal and, if it is not made, the genes that could code for it may still be present in the animal. Simulating the gene libraries by collections of bitstrings that then get sampled and pieced together to make variable regions, Forrest, Hightower, and Perelson have shown that evolution can act on the gene libraries in a population of individuals, even when the libraries are being being randomly sampled. Their work provides a quantitative attempt to assess how well evolution will work in an environment with high sampling noise.

7.2 Modeling Somatic Mutation of Antibodies During the Course of an Immune Response

T. Kepler and A. Perelson

One of the adaptive features of the immune system is that, during the course of an immune response, antibodies are mutated rapidly in an attempt to improve their binding for the immunizing antigen. This rapid mutation process, called somatic hypermutation, is controlled by an unknown mechanism. Perelson and SFI Postdoctoral Fellow Thomas Kepler have examined the mutation process as an optimal control problem and have asked how should mutation be controlled to maximize the total binding affinity for the antigen. They discovered that mutation should remain off early in the response, then be turned on and off in a cyclic manner a number of times. Assuming, say, that only one mutation in a hundred increases affinity , one can see that with the algorithm, the cells initiating the response are allowed to grow to clones of size of order 100 so that, when mutation is turned on, at least one improvement mutation is found. Once this improvement is generated, mutation is turned off to allow the mutant clone to grow. Perelson and Kepler have proposed that this cycling of mutation has an anatomic basis, with cells mutating in the dark zone of the germinal centers and then moving to the light zone where they proliferate. To start the next cycle the cells then would have to reenter the dark and repeat the process. The movement of cells between the dark and light zones of the germinal center has been observed, and the suggestion of cyclic reentry is seen to be reasonable by a number of experimentalists who are seeing if they can verify the suggestion.

7.3 Modeling Immune Networks Using Novel Computer Simulation Techniques to Determine Whether They are Capable of Generating Immune Responses

G. Duchateau, R. De Boer, A. Neumann, A. Perelson, R. Rose, and G. Weisbuch

The pattern recognition capabilities of the immune system are so great that the system can recognize the unique features of its own antibodies, their idiotopes. Because of idiotypic recognition, Jerne suggested that the immune system is organized as a network of interacting cells and molecules. To test these ideas, SFI External Faculty members Rob De Boer, Gérard Weisbuch, and Alan Perelson, together with SFI postdoctoral fellow Avidan Neumann, Ecole Normale postdoctoral fellow Guillemette Duchateau, and SFI undergraduate student Randall Rose have developed a number of different models of the immune network and studied their properties.

Measurements of the concentration of an antibody and its anti-idiotype have been made by the Coutinho group in Paris. These measurements show that concentrations in unimmunized mice fluctuate randomly, maybe even chaotically. Dynamical models containing both B cells and antibodies have been studied in great detail using methods from nonlinear dynamics. Parameter regimes have been discovered in which the model gives dynamical behavior similar to that observed by the Coutinho group. Other behaviors have also been observed in the model and suggestions made for experimental tests. One question that the Coutinho group has raised is whether immune networks can give rise to immune responses. If interactions between the elements of a network are very strong, then the behavior of the elements may be determined by these internal interactions and not be very sensitive to antigenic perturbation. Using an antibody B cell model, we have shown that even when random fluctuations dominate a network, the network can respond to antigen and eliminate it. However, in our model, network responses are not as vigorous as those observed in an animal and so far we have not been able to duplicate the typical kinetic seen in primary and secondary immune responses. We are now exploring a novel class of models in which B cells respond to the level of receptor crosslinking and to the rate of change of crosslinking. We believe that if B cells can sense rates of change, they should be able to distinguish between ongoing internal activity in an network and antigenic perturbations

Rose has begun work on implementing the computer model on high-performance vector computers so that simulations can be run in realistic parameter ranges where stiffness of the equations, due to the existence of multiple time scales, is a problem. In the summer of 1992 Rose attended a six-week workshop given at Los Alamos National Laboratory on the use of high-performance computers such as the CRAY Y-MP and Thinking Machines CM-5.

Neumann's work concentrates on autoimmune diseases such as systemic lupus erythematous (SLE) and multiple sclerosis (MS). Experimental results recently obtained for SLE disease show that the idiotypic network has a functional role in the development of this autoimmune disease. Using the idiotypic network model, Neumann is studying the theoretical basis for the development of SLE and other related diseases. In a related effort he is working on constructing schemes for experiments that will give better data on the structure of the immune network and will shed light on the functional role of the idiotypic network in normal immune response.

Weisbuch is studying the capacity of the immune system to cope with the presentation of a large number of antigens during the life of the animal. The aim is to answer questions such as how many antigens can be tolerated or vaccinated. When new antigens are presented, what happens to the antigens that are newly presented and what happens to antigens that were already tolerated or vaccinated? Weisbuch is also working with Guillumette Duchateau on a model they have developed based on a system of differential equations that were solved using GRIND software. They have showed that differences in rejection rates of parasites and true symbionts by the host account for the emergence of mutualism. This approach may be closer to modeling actual living systems such as coelenterates than models based on the iterated prisoners dilemma or core wars. The model will be extended to take into account the existence of different compartments and different rejection rates of coelenterates.

7.4 Modeling Immune Responses to Tumors

A. Kunetsov and A. Perelson

Alexander Kunetsov visited SFI for several months early in 1992 and collaborated with Alan Perelson on dynamic models for natural killer cells' (NK cells) recognition of target cells (TC). One of most notable features of NK cells is their ability to recognize and destroy quickly (for 0.1–2 hours) tumor cells of various origin, virus-infected syngenic cells, and aged cells. NK responses take place without preliminary induction by an antigen or mitogen. Unknown are the intermediary mechanisms of recognition by cytotoxic cells of such a wide range of target cells (TCs).

A novel hypothesis is formulated of NK-like recognition of target cells; such recognition does not assume the presence of a specific receptor on NK cells. According to this hypothesis, the following are necessary for recognition:

1. the presence of various kinds of receptors and their ligands (anti-receptors) associated with the plasma membrane of an NK cell and/or target cell;

2. presence of disorders in the organization of the target cells' membrane framework complex of cytoskeleton;

3. transfer of membrane fragments and pieces of framework cytoskeleton by means of exocytosis from the surface of one of contacting cells to the other; and

4. strong adhesion of NK cell with the TC using free-receptor and anti-receptor sets presented on the contacted cell surfaces.

Within the framework of this model of recognition of TC by NK-like cells, it appears possible to explain the nature of wide polymorphism of TCs sensitive to the effect of NK-like cells, as well as a number of nonlinear effects in the NK-cellular reaction to modification of structural and dynamic surface properties of an NK-like cells or TCs.

The analysis of a corresponding mathematical model of a cytotoxic reaction of NK cells has shown that it reflects well both qualitative and quantitative aspects of the cytotoxic process and explains the effects of inhibition of the cytotoxic reaction at great ratios of effector cells to target cells. Scenarios have been presented of possible experiments testing the adequacy of the concept suggested and its practical application.

Kunetsov and Perelson also working on formulating a novel mathematical model of NK-cell–TC interactions. In this model they take to account (1) the turn on threshold character of cytotoxic mechanisms after than strong cell-cell contact becomes enough and (2) the TC capacity for inactivates of NK-cell functions. This mutual research on the model will be continued.

8. THEORETICAL NEUROBIOLOGY

D. Baylor, C. Gilbert, V. Gremillion, N. Kopell, R. Ranganathan, C. Stevens, and M. Stryker

Understanding the complexities of the brain demands sophisticated theoretical approaches. Yet a comprehensive theoretical neurobiology does not exist. In mid-1992 Charles Stevens (Salk Institute) and Michael Stryker (UC San Francisco) convened a working group of experimental and theoretical neurobiologists to try to stimulate intradisciplinary collaboration in this field. The goal of the meeting was both to begin an evaluation of the state of theory in neurobiology, and to start identifying research areas in which a combination of theory and experiment might contribute most to our understanding of brain function.

Eighteen neuroscientists visited SFI over five weeks in June and July. The group was mixed: half were senior scientists, half, junior; half were theorists, complemented by an equal number of experimentalists. Everyone, however, works on problems relating to the visual system. This topic was selected because understanding of brain structure and function is most advanced for vision. Also, visual system problems have traditionally been attractive to theorists. Daily talks aimed at uncovering common ground: the theorists presented an extensive summary of theory in visual neurobiology—although the field is far from complete—and the experimentalists in turn described phenomena in need of theoretical descriptions. Topics included approaches to understanding primate vision; minimum entropy as a design principle for sensory processing; temporal organization of spike trains; calcium effects in visual transduction; dynamic properties of the visual cortex; modeling and classification of neural signals; multineuronal signals from the retina; and models for self-organization of cortical maps.

Although no existing theory has yet materially changed the understanding of the brain, the group feels that theoretical approaches are on the verge of doing so. They also agree that the theories with the most potential in that regard share a common feature: they relate to some general principle that governs brain structure, function, or development. One general rule, for example, is that the brain uses knowledge about properties of the world (recorded in its circuit organization and in the dynamic neuronal properties of neurons by evolution and by plasticity mechanisms that operate in development) to solve problems for which insufficient information is available from the environment. This principle provides the basis for a theoretical account of retinal receptive fields: information placed in the structure of the retinal circuits by evolution can be used to compensate for defects in the eye's optics, and the computation the eye must do to make this correction explains the retinal field structure. The fact that theories using general principles are beginning to successfully account for common experimental observations points the way to a growing maturity in neurobiological theory.

Several collaborations immediately resulted from last summer's meeting. Marcus Meister, for example, has developed a unique technology that lets him monitor the activities of many neurons at the same time. His experimental methods are very useful in testing the recently proposed theory of Joseph Atick and Norman Redlich on retinal processing. An experiment that developed out of the Santa Fe meeting is to measure the simultaneous response of many retinal output neurons when the retina is stimulated by natural images. The theory predicts that the output exhibits a pattern of statistically independent activations. The experiment of Marcus will be able to test whether this is the case in actual retinas.

Self-organization of neuronal circuits during development was one of the recurrent themes during the workshop, and Charles Gilbert (Rockefeller University) and Charles Stevens began a collaboration in which they use detailed information, gathered in Gilbert's laboratory, on the distribution of synapses—the points of contact between nerve cells at which information is exchanged—in the visual system. Their goal is to develop a refined version of current theories of how this self-organization takes place. The detailed data on synapse distribution should permit decisions to be made between several existing ideas about the mechanisms of self-organization.

In another effort Rama Ranganathan (UC San Diego), Dennis Baylor (Stanford), and Stevens teamed up to construct a theory for the initial steps in phototransduction, the process through which eyes change patterns of light into nerve signals. Ranganathan had new data on phototransduction in eyes from mutant fruit flies that lack a crucial protein known to be involved in the process. The responses of the mutant fly eyes gave clues for how normal transduction works, but a theory was needed to interpret the data. Ranganathan and Baylor have done some experiments last fall that provide data for testing this summer's theory, and the results are being evaluated now.

The group reconvenes in the summer of 1993, led by Stryker and Nancy Kopell (Boston U.). The working title for one of the two planned ten-day meetings is "Dynamic Control of Stability and Flexibility," focusing on how the central nervous system comes to be organized so that it is capable both of flexibility and robustness. This theme touches on questions at many different levels of organization and time scale, from rapid signals among neurons to neural development. Questions range from how properties at the level of cellular biophysics affect emergent network behavior to how learning within a network can be done in a stable manner. The goal of the workshop is to survey the mechanisms of motor control, from properties of individual cells to the emergent properties of networks, and to identify those parts of the problem that are amenable to theoretical analysis. A preliminary list of participants (in addition to the organizers) includes L. Abbot, A. Bekoff, H. Chiel, B. Ermentrout, S. Lockery, M. Sompolinsky, and T. Williams.

Stryker's workshop will focus on visual object recognition. Several laboratories have recently been defining the properties of neurons in cortical regions that are several processing stages beyond the primary visual area and that possess complex receptive fields (like selective responses to faces and face components). The goal of the workshop is to define the theoretical issues involved in understanding how these complex receptive fields could be constructed and to explore the implications the existence of these receptive field types have for pattern recognition. A preliminary list of participants (in addition to the organizers) includes S. Zucker, W. Bialek, C. Koch, Y. Miyashita, K. Tanaka, S. Ullman, S. Edelman, W. Newsom, J. A. Movshon, and T. Sejnowski.

In related work, Valerie Gremillion (UC San Diego and LANL), in residence at SFI on a part-time basis throughout 1992, conducted thesis research on the spatio-temporal encoding of information in the nervous system. She performed simulations of the cat visual pathway, including appropriate cellular dynamics, three-dimensional structure, and connectivity patterns, in order to determine the circuitry necessary to generate specific properties of receptive fields. Her particular interest lies how system geometry and connectivity interact to produce larger-scale patterns, and in how excitation and inhibition interact in large circuitries and feedback networks.

9. ECONOMICS AS A COMPLEX ADAPTIVE SYSTEM

9.1 Core Program

Resident directors in 1992: M. Shubik and B. LeBaron
Steering Committee of the Economics Program: P. Anderson, K. Arrow, W. B. Arthur, W. A. Brock, J. Geanakoplos, M. Gell-Mann, J. Holland, D. Lane, B. LeBaron, R. Palmer, D. Pines, D. Rumelhart, J. Scheinkman, and M. Shubik

Under the direction of Martin Shubik (Yale) in the first half of 1992 and Blake LeBaron in the latter portion of the year, research in economics as a complex adaptive system continued at SFI. This work characterizes the economy as composed of large numbers of interacting agents, mutually adjusting to each other as time passes: the economy is a massively parallel system that is continually adapting. The agents in this economy—the "interacting particles" of economics—decide their actions consciously, with a view to the possible future actions and reactions of other agents. That is, they formulate strategy and expectations. In doing this they may be faced with complicated and possibly ill-defined problems that are far beyond the scope of normal human intelligence to solve completely. Hence they are often forced to act inductively: they form internal models; they transfer experience from other, similar problems; they generalize from limited data; and they learn as they go. As this learning and mutual adaptation take place, sometimes new economic structures emerge, and there is a continual formation and reformation of the institutions, behaviors, and technologies that comprise the economy. Some parts of the economy may be "attracted" to an equilibrium; some parts may continually evolve and never settle The central task of the SFI program is to develop the methods and to formulate and solve the demonstration problems that articulate this picture of the economy.

As part of its core Economics Program activities focusing on learning and adaptation, SFI sponsored in May, 1992 the workshop "Biology and Economics: Overlapping Generations." The meeting was chaired by Martin Shubik (Yale) and was made possible by support from the Gordon and Ann Getty Foundation. A key problem in biology, economics, and demography is understanding the mechanisms controlling the growth and evolution of population and the intergenerational transfer of resources. This workshop brought together biologists, economists, and anthropologists to focus on this issue and compare approaches.

Some economists, for example, focus on human capital and consider family size selection, marriage, education, health, and old-age care from the viewpoint of consumers optimizing investment in human capital. Other economic theorists considering overlapping generations models of the economy are directly concerned with economic solutions for glueing the generations together and seeing how far market and financial mechanisms can be used to transfer resources from generation to generation by individuals with little or no social concern. Some biologists, along with game theorists, have developed evolutionary models of the "selfish gene" where the central actors are the genes, and the *Homo oeconomicus* of the economist becomes a mechanism being run by the real players, the optimizing genes. Yet a different viewpoint is provided by demographers, sociologists, and anthropologists who have a mixture of models of human society where births, deaths, and population growth are accounted for by a variety of biological, economic, sociological, and cultural factors.

Some of the questions considered during the workshop were: how far can the models based on individual selfish optimization be pushed? What is being optimized by whom? Do the concepts of human capital and wealth have clean analogies in biology? Are culture and even the financial network of an economy exoneural networks that provide control mechanisms on individual selfish humans in a manner that has no close counterparts in the evolution of other species?

Several working groups function within this core portion of the Economics program. The "Interacting Particles in Economic Modeling" group is analyzing the explicit modeling of large economic systems as interactions of many small individual components. Some examples of this research are interconnected production and inventory systems, and the sharing of information in financial markets. This group directly uses techniques taken from statistical mechanics and work on self-organized criticality. Members include Buz Brock (Wisconsin) and José Scheinkman (U. Chicago).

The "Evolutionary Finance" working group is exploring evolution and learning in financial markets. This novel approach to finance explores trading strategies and forecasting behavior in an evolutionary setting where strategies interact with others. Members include Larry Blume, Richard Easley and Andy Lo.

Alongside the central themes of the SFI Economics program of interactions among agents, massive parallelism, dynamics, adaptation, and emergence are the following three partially overlapping, peripheral topics.

9.1.1 Nonlinearities

B. Arthur, D. Lane, and M. Shubik

Nonlinear mechanisms and positive feedbacks are normally present in the economy, but they have been relatively little researched. Today's economies are no longer based on agriculture and bulk manufacturing, but rather on high-technology industries and increasingly sophisticated services. High-technology products—like new pharmaceuticals, Cray computers, or Microsoft Windows—share the property that most of their costs are up-front R&D investment costs. The more market they capture, the lower their per-unit costs. Hence they show positive feedback or "increasing return" to market share. The correct characterization and understanding of increasing returns is one of the key problems in economic theory and practice.

A variety of analytic, computational, and empirical issues relating to increasing returns was the focus of a 1992 SFI workshop chaired by Martin Shubik. Among other topics, participants considered a model developed at SFI by External Professors David Lane and Brian Arthur: The model posits a group of new products are competing for adoption. Each potential adopter decides which of the products to choose on the basis of their prices, which he knows, and performance characteristics, about which he is imperfectly informed. To augment the publicly available information about the products, he samples in addition some of the previous adopters, finding out from each which was adopted and some information about how well the product has performed. Clearly, in this situation, more information is likely to be generated about the products that have been more frequently adopted. Can this informational feedback lead to increasing returns—that is, can a product increase its market share solely on the basis of the information effects of its current market lead? The answer is "sometimes" and it turns out to depend in subtle (but quantifiable) ways on certain psychological characteristics of the adopting agents. In this model, chance enters the picture through the sampling procedure whereby agents acquire information; thus, who learns what from whom constitute the "small events" that determine whether one or another of the products dominates the market or whether they ultimately share the market with one of the (generally very few) stable frequency allocations that can be computed from the agent and product characteristics that parameterize the model.

9.1.2 Pattern Formation
M. Shubik

Closely overlapping with the above theme is that of pattern formation—the emergence of new, sometimes unexpected macro-structures from the micro-interactions of firms, industries, and financial agencies. Of interest here is the formation of cooperative structures over time and the "selection" of one from many possible potential candidate structures by processes of adaptation.

In work that falls both under core program concerns and in this area, Shubik led several working group meetings focusing on the theory of money and financial institutions. The group wants to understand the basic structure and role of various financial instruments and institutions—in particular, fiat (or outside) money, inside monies or credit, and bonds. The research seeks to clarify how interest rates are determined (and what leads to the term structure of interest rates) and how markets and financial institutions function. In particular, what is a minimal set of instruments and institutions needed to run an efficient economy—and what costs are incurred by a society for which some of these elements are missing? The work draws on the expertise of economists, learning theorists, and computer modelers, as well as the mathematics of stochastic processes, dynamic programming, and game theory. Members of this continuing working group are Robert Anderson (UC Berkeley); Predeep Dubey (SUNY Stony Brook); John Geanakoplos (Yale); Yannis Karatzas (Columbia); John Miller (Carnegie-Mellon); Lloyd Shapley (UC Los Angeles); Martin Shubik (Yale); and William Sudderth (Minnesota).

The approach adopted to these questions rests on the concept of strategic market games. These are economic process models that are constructed as playable and potentially experimental market games. In these games, price formation mechanisms, markets, and financial instruments are explicitly specified. Thus they can serve as testbeds for behavioral simulations where the performance of human and artificial agents can be compared to the predictions of noncooperative equilibrium and general equilibrium theory. Preliminary work already shows paradoxical results concerning the relationships among monetary wealth, stocks and flows of money, and the needs for and nature of bankruptcy rules to define the treatment of unpaid debts in a dynamic system.

Two research papers have been completed; the first by Karatzas, Sudderth, and Shubik is entitled the "Construction of Stationary Markov Equilibria in a Strategic market Game." It has appeared as an SFI Working Paper and is now being revised and enlarged. It makes precise the Keynesian concept of precautionary reserves. A second paper, by John Miller and Martin Shubik, is entitled "Some Dynamics of a Strategic Market Game with a Large Number of Agents." It, too, has appeared as a SFI Working paper.

9.1.3 Empirical Research
D. Dechert, R. Gencay, C. Hiemstra, B. LeBaron, J. Miller, R. Palmer, S. Potter, and J. Rust

The SFI program emphasizes the formulation of assumptions from rigorous observation of actual, human economic behavior. This entails observation and analysis of human behavior in bargaining situations, in financial markets, and in experiments in economics laboratories. And it entails the participation of psychologists and others who know how human decision-making actually works.

The Arizona Token Exchange project, co-sponsored by the University of Arizona's Economic Science Laboratory and the Santa Fe Institute, compares the performance of human and program traders to see whether humans can learn to exploit the limitations and idiosyncracies of computers in repeated interactions. This program is the continuation of work by John Miller (Carnegie-Mellon), Richard Palmer (Duke), and John Rust (U. Wisconsin) on double auction markets and trading strategies begun at SFI in 1989.The AZTE is a computerized market in which a fictional commodity called "tokens" are traded. The market is a simplified version of commodity exchanges such as the Chicago Board of Trade where buyers and sellers are able to call out bids and asks to buy or sell units of the commodity. In each trading session on AZTE, traders are assigned the role of buyer or seller and are given an allocation of tokens. A seller's objective is to sell their tokens for as much as possible above the token cost and a buyer's objective is to buy tokens as cheaply as possible below their redemption value.

By ranking the token costs and redemption values, well-defined supply and demand curves can be constructed. The intersection of these curves defines the so-called competitive equilibrium (CE) price and quantity, at which neoclassical economic theory predicts all trading will occur. The complication is that in the AZTE, each trader's token costs and redemption values are private information and differ from trader to trader. Thus traders in the AZTE face a complex sequential decision problem: how much should they bid or ask for their own tokens, how soon should they place a bid or ask, and under what circumstances should they accept an outstanding bid or ask some other trader? An additional complication is that each trading session runs for a fixed amount of time. This creates a difficult trade-off, for if traders spend too much time looking for a good deal, they may find themselves locked out of the market without trading anything.

Unlike real commodities markets where most traders are humans, in the AZTE human competitors play against computer programs. The program traders range in sophistication from simple rules of thumb (such as the Gode-Sunder "Zero-Intelligence" strategy) to sophisticated optimizing/learning algorithms (such as neural nets and genetic algorithms) developed from the recent literature on artificial intelligence.

A related book, an edited proceedings volume resulting from a 1991 meeting on the double oral auction work, was published early in 1993.

William Brock (U. Wisconsin) and LeBaron both are working on several different problems related to economic time series. Brock has been working on formulating and estimating new models of interacting trader behavior. These models, based on statistical mechanics foundations, are formalized to give empirically tractable restrictions on the joint movements of prices and volume. These restrictions are then used to estimate the model parameters from actual time series data. LeBaron has continued his work on the issue of economic time series predictability as related to moving average technical trading rules. He is looking at the types of stochastic processes that are consistent with the predictability found in these markets from simple rules followed by traders. His initial findings indicate that some types of trading rules are more closely related to long-range trend behavior rather than nonlinearities. LeBaron is also continuing work on the joint dynamics of prices and trading volume. The goal of this work is to uncover patterns that are not consistent with standard models for volume and price comovements. These results help to clarify what structures different models of price/volume movements will need to contain to explain the behaviors observed in financial markets.

The "Time Series" research network is working on detecting the presence of underlying behavioral patterns in time-series data that are often highly corrupted by noise. Members include Dee Dechert (U. Houston), Remo Gencay (U. Windsor), Craig Hiemstra (Loyola) and Simon Potter (UC Los Angeles). Standard economic theory suggests that many series of interest—financial series, for example—should show no pattern at all: they are merely random walks. This in fact does not appear to be the case. One of the most important products of the SFI Economics Program, in fact, is the development of methods that detect underlying patterns and that use these to predict. Using the machine learning techniques of John Holland, John Koza, Doyne Farmer, and other participants, Santa Fe has pioneered approaches that seek out the real behavior in markets and that contrast this with imagined, theoretical behavior. This group frequently joins forces with Institute researchers working on low-dimensional chaos with the aim of reaching a synthesis on recent results on time series work from economics, medicine and other fields.

9.1.4 Computation

SFI is a center for novel computation techniques in economics relating to learning and adaptive agents. In this capacity SFI sponsored the "Theoretical Computation in Economics" workshop held at the Institute in April 1992. The meeting was chaired by Michele Boldrin (Northwestern) and John Miller (Carnegie-Mellon). The Alfred P. Sloan Foundation, National Bureau of Economic Research (General Equilibrium Program), and National Center for Supercomputing Applications (U. Illinois, Urbana-Champaign) joined the Institute in the sponsorship of the conference.

The new computational tools not only complement both existing theoretical and experimental methods, they also hold promise of a number of new opportunities for productive analysis. One obvious application is the analysis of existing theoretic models. Economists have developed a large set of models. Using standard analytic techniques, they have been able to derive the basic properties of these models, including: the existence of equilibria, the qualitative properties of such equilibria, some notions of the model's dynamics, the relationship between the model and real-world data, etc. Nevertheless, the preservation of analytic tractability has required a variety of compromises, including excessive aggregation, the simplification of some possibly important features, and often times only the proof of existence but not necessarily the ability to derive the qualitative properties of the equilibrium solution. To go beyond these limitations, it is likely that computation-intensive techniques must be used. Another application of computation is the estimation of appropriate parameter values for the theoretical model.

A complementary field of inquiry is the use of computer-based techniques as the core of the model. These models release researchers from traditional analytic bounds and allow them to explore systems which heretofore have not been easily modeled by existing techniques. Although this area is new, a number of interesting findings have already been made. This modeling approach also offers other opportunities. The methodology creates an easily manipulated model world in which one can generate and test theoretical hypotheses. It also suggests a new direction for economic theory whereby theoretically plausible models of economic behavior are formulated and then placed in an easily implemented empirical framework. Beyond the above, this methodology has a practical application to some important real-world phenomenon. For example, computer techniques provide opportunities to study auction markets. Some questions that can be explored are: what are their stability properties, can strategies be exploited, and what types of strategies will do well in these markets? One can also test new institutional designs with artificial agents before actually implementing the markets.

10. EVOLUTION OF HUMAN CULTURE

M. Diehl, M. Gell-Mann, G. Gumerman, and T. Kohler

Two complementary areas of the Institute's work—research on the growth, centralization, and dispersion of cultures in the prehistoric southwest and SFI's work on developing models and simulations of organizations—are converging to form a more comprehensive SFI program which will focus on the evolution of organizations through time.

"Resource Stress, Economic Uncertainty, and Human Response in the Prehistoric Southwest," held in February 1992, was the second SFI workshop to study prehistoric Southwestern societies as complex adaptive systems. The first, held in the fall of 1990, followed a series of advanced seminars at the School of American Research. This most recent meeting, co-sponsored and funded by the U.S. Forest Service as part of its new program in archaeological research in the Rocky Mountain region, was chaired by Joseph Tainter (USDA Forest Service).

What is intriguing about this work on cultural evolution is that it looks at the archaeological record to try to understand if the forces that underlie the rise and fall of societies, in this case a local one, can be correlated with fluctuations in available resources. In a world where predictions are regularly made about the consequences of use patterns of natural resources, it seems instructive to understand better how use patterns related to societies in the past and what forces have led to the collapse of flourishing societies.

The February meeting focused on two issues. The first topic, factors of vulnerability, focused on matters such as population trends, climate change, degree of aggregation, availability of naturally occurring foods, agricultural successes and failures, and the costs of supporting political, economic, and ritual systems. The second issue, strategies or failure of adaptation, dealt with subtopics such as increases or decreases in socio-cultural complexity, aggregation/dispersion, local/regional abandonments, range expansion/contraction, subsistence shifts and intensification, technological change, economic specialization, and population decline.

Recurrent themes throughout all the talks were risk and variety. Prehistoric Southwesterners were flexible in their adaptations to a risky environment. Their responses included social arrangements for sharing; adjustments to anthropogenic changes; use of famine foods; storage; technological adjustment; environmental manipulation; strategies for obtaining protein; and strategies for settlement relocation.

Plans are being developed for two additional conferences. The first will probably be in 1993 and will deal with the same topic in the North American eastern woodlands. The second will be held in Austria in Fall 1993 and will address the topic internationally. Proceedings from the 1992 meeting will be published as part of SFI Studies in the Sciences of Complexity book series.

Tim Kohler's (U. Washington) work centers on the question of why prehistoric agricultural groups in many areas of the Southwest oscillate between dispersed and aggregated settlements until about A.D. 1300, but remain in aggregated settlements (pueblos) after that time. He is approaching this problem by thorough analysis of the changing temporal and spatial structure of resources (using geographic information systems), microeconomic models, and Swarm intelligence.

Kohler is also investigating the possibility of using cellular automata to model the interaction of households as nodes in a network (an ideal prehistoric village) in which households have limited and somewhat biased connections to other households in the network. Here the interest is in seeing what kinds of attractors might appear. Reciprocity is such a stable and widely distributed system that it may well turn out to be one such attractor.

Michael Diehl (SUNY Buffalo) is at the Institute through May 1993 as a predoctoral fellow in SFI's Cultural Evolution/Southwest Prehistory program. His work resonates with Kohler's on prehistoric village formation.

Some human societies rely on subsistence resources that are spatially patchy, temporally unpredictable, or easily overexploited. Based upon limited ethnographic data anthropologists have suggested that in such situations competitive accumulation of goods to enhance personal prestige or wealth is socially suppressed. Status competition destabilizes social relations among people who are highly interdependent, and can lead to the destruction of the resource base through overconsumption. Is social suppression of status competition typical of groups who rely on unpredictable or easily overused resources?

Diehl's work compares attributes of the subsistence economies of the Early Pithouse (A.D. 200–600) and Late Pithouse (A.D. 600–1000) periods of the Mogollon region of the prehistoric Southwest. He is also looking for evidence of extreme differences in household possession of items that may have been used to mark status or prestige. By assessing changes in parameters of subsistence and wealth, he can determine whether unequal accumulation of prestige enhancing items became more acceptable as prehistoric Mogollones increasingly relied on a more stable and productive resource base.

This research is important for anthropologists who attempt to model the emergence of formalized leadership positions, because many scholars have observed that chiefs, religious leaders, formal ruling class members, or less formally empowered "big guys" get and build power in part by ostentatious display of rare goods, and by competitive accumulation and consumption. Diehl's work will contribute to the discussion by assessing whether the emergence of privileged leaders is an inherent tendency of human societies.

SFI's initial research in prehistorical culture is leading to a broader approach which extends from the origins of human cultural behavior to state-level societies, including an exploration of the implications for advanced societies of the findings about simple societies. One step in this direction is the work of Wolfgang Fikentscher (U. Vienna) who was in residence at SFI for three months in 1992, researching the ethnography and anthropology of law and focusing on the Rio Grande Pueblos. This field work consisted of interviews with tribal judges and court administrators. The theoretical side of the research concerns aspects of cognitive anthropology, tribal organization (especially the moiety structure of the Tewa Pueblos), and other Pueblo characteristics in comparison with other Native American tribes. Certainly this broader-based approach will involve moving beyond the data from the Southwest, which is largely derived from a superb suite of artifacts, to combinations of historical and physical records from places like the Roman Empire, or more modern census records from China and India.

This approach to evolution of culture may focus on study of the emergence of collective behavior from independent agents whose actions are based on evolving individual schemata, leading to the evolution of social structures. Other important features might include the unintended consequences of the actions of independent agents, incorporation of biological traits in the models, cultural transmission of traits, the role of migration and the significance of linguistic diversity, and so on. (It is important to recognize that the agents in a cultural model might not be individuals but might be larger society units such as clans, villages, or economic sectors.) This approach will require modeling platforms, like SSS, that are sufficiently general to allow different researchers to view these very different problems.

This work might best be done first in a general context, understanding the problems at a general-process level, and then proceed to a more detailed level. It is likely that a working group on the evolution of culture will be formed during a 1993 summer meeting of the SFI External Faculty.

Complementing this comprehensive approach is a parallel initiative that is focusing specifically on evolution and learning in modern organizations.

In March 1992 the Institute held a workshop Adaptive Process and Organization, co-chaired by Michael Cohen (Institute of Public Policy Studies, U. Michigan) and David Lane (U. Minnesota). The meeting drew 25 participants, social scientists drawn from university departments of economics, political science, and sociology, from schools of business, from the government, and from the private sector. Those from other fields were mathematicians, computer scientists, physicists, and theoretical biologists who have developed tools to model complex adaptive systems.

The group experimented with a novel format. Seven papers were distributed and read in advance. Each provided either a model or data that might stimulate the group. Five papers were by social scientists (John Padgett, Karl Weick, James March, Robert Axelrod, and Michael Cohen). Two were by non-social scientists (John Holland and Stuart Kauffman). The papers were presented to the group not by their authors, but by another participant who hailed from some quite different field. So, for example, Gérard Weisbuch presented Axelrod's paper on coalition formation and drew out its connection to spin glass and neural net models. Dan Levinthal presented Kauffman's paper on biological NK models,and showed its relation to work on business strategy and technological innovation. Les Glasser connected Weick's study of carrier flight-deck crews to issues arising in distributed artificial intelligence. This worked to create a common ground for discussion quickly. The result was a substantial gain for the group, who had a shared awareness of definite and relevant data and models that could be referred to in the discussions that occupied the remainder of the meeting.

Two broad domains of discussion emerged, each with rich potential for further collaboration. The first centered on models that shared a common root metaphor of adaptation as landscape exploration. Several participants interested in these landscape models found it promising to explore their common fascination with technological innovation in economies. Levinthal and Kauffman may work along these lines. Introduction of Hebbian rules into economic and political landscape models, suggested also by Weisbuch, turned out to be quite interesting to both Axelrod and Levinthal. The second, sometimes referred to as the "structuralist" concern, centered on how multiple agents interact to give rise to a superordinate entity with its own coherence, that may in turn constrain the subsequent actions of the lower-level agents. Weick, Padgett, Leo Buss, Holland, and Axelrod are especially interested in pursuing questions about the emergence and persistence of organizational entities. There is also strong interest in convening at SFI a working group to spend an extended period of time on one or two projects/data sets ready to support collaborative, interdisciplinary analysis.

It has been noted that in the real world, high-technology firms don't operate according to the classical theory of the firm (echoing much of the SFI External Faculty Member Brian Arthur's work on why knowledge-based companies respond to markets differently than resource-based companies). SFI plans to further consider these modern innovative enterprises, which are examples of rapidly evolving complex adaptive systems and may be particularly amenable to study. Specific topics may include research into the relation of selection pressures to the evolution of an organization, particularly because selection pressures on individuals within firms can vary significantly from selection pressures on the firm itself; here there are obvious parallels with biological communities and ecologies. This work could shed light on our understanding of why modern organizations seem to break so catastrophically.

Possible case studies may be the evolution and learning in government bureaucracies; change in military organizations, which tend to be introspective because they mount formal analyses of failures and successes; and perhaps the study of university organization. A segmented approach might be appropriate, one that would be specific to corporations and other organizations by class but that would then include cross-organizational aspects. Kenneth Arrow and Murray Gell-Mann have agreed to co-chair a founding workshop on adaptation and evolution in modern organizations.

11. EDUCATIONAL ACTIVITIES/OUTREACH

Since its founding, the Santa Fe Institute has been committed to a program of education in the sciences of complexity. With an innovative undergraduate internship program, co-sponsorship of the graduate-level Complex Systems Summer School, and graduate student residencies for thesis research, along with its sponsorship of postdoctoral residential research, SFI pursues a program of complex systems education at all academic levels.

11.1 Complex Systems Summer School

The purpose of the Summer School on Complex Systems, begun in 1988 and held annually each summer in Santa Fe since then, is to provide graduate students and postdoctoral fellows with an introduction to the study of complex behavior in mathematical, physical, and living systems. Because of its relative newness and interdisciplinary nature, the subject of complex systems is not easily accessible to researchers as a whole and to students in particular. The School is intended to address the need for a coherent and substantive presentation of the concepts and techniques emerging in this area. It attracts, stimulates, and educates the best young scientists as they begin to define their own research programs.

To date, the School provides the only offering of this kind in the nation. While several universities, including some of the sponsoring institutions of the Summer School, are beginning to establish centers for research and teaching in complex systems, strong programs around the country are still several years in the future.

The School is co-sponsored by a group of institutes, centers, and universities throughout the country, with the Santa Fe Institute acting as fiscal and administrative agent. The Center for Nonlinear Studies at Los Alamos, Sandia National Laboratories, and the Universities of Arizona, California, Illinois, Maryland, New Mexico, and Texas have joined SFI as sponsors for this School. In addition, other universities provide financial support for their students in attendance at the school. In this category are Brandeis, Columbia University, Princeton University, Stanford University, the University of Pennsylvania, and Yale University. Support was also received in 1992 from the Department of Energy, the National Institute of Mental Health, and the Office of Naval Research.

An Organizing and Steering Committee representing the consortium of sponsors provides general guidance for the effort and oversees the selection of the School's Director(s), who vary from year to year. The 1988 School was led by Daniel Stein (U. Arizona); Erica Jen (LANL) directed the 1989 meeting; Co-Directors for the School since 1990 have been Daniel Stein and Lynn Nadel (U. Arizona). By virtue of administrative experience with the School and because Santa Fe is a prime site for such a summer activity, it is the consensus of the sponsoring consortium that the likelihood is great that the Complex Systems Summer School will continue to be run in Santa Fe by SFI.

The emphasis in the school is on combining the understanding of phenomena derived from traditional approaches with that gained from the novel ideas of complex systems. To this end, the school focuses on developing techniques for measuring and analyzing complex behavior and applying these techniques to the study of a limited number of specific mathematical, physical, and living systems. The school usually consists of approximately nine to twelve short courses together with a number of seminars on selected topics. Specific foci vary with the director and faculty, but typical topics are nonlinear dynamics, computational and algorithmic complexity, cellular automata, fluid dynamics, disordered systems, neural nets, adaptive learning algorithms, cognition, molecular biology, physiology, neurobiology, evolution, pattern formation in biological systems, and the design of parallel-processing algorithms.

In addition to their formal lectures the faculty are available during the day for informal discussions with the students and frequently schedule supplementary tutorial sessions in the evenings. A computer laboratory containing a range of desktop microcomputers, workstations, and graphics devices is an integral part of the school. Students and faculty bring software to supplement that installed on the network. Students are encouraged to organize their own research groups and student seminars are a common feature of the self-organized part of the program.

Between 50 and 60 students attend the school each year; applications typically are double the number of students accepted.

The schools have several important long-term outcomes. One product of the Schools is lecture note volumes. These texts, which have appeared annually since 1989, are intended to provide an introduction to a broad range of topics and may well become a standard reference in the sciences of complexity. The lectures from the 1992 school currently are being edited by D. Stein and L. Nadel for publication in July 1993.

Summer School alumni, including Robert Axtell, Aviv Bergman, Bill Bruno, Stephanie Forrest, Neil Gershenfeld, Wentian Li, John Miller, and Andreas Weigend, have gone on to conduct research at SFI, and the schools have also played an important role in introducing more senior scientists to the Santa Fe

Institute. Several members of the Institute's research community—including Jay Mittenthal, Joe Traub, Peter Wolynes, and Bernardo Huberman—initially came to Santa Fe as Complex Systems Summer School faculty.

11.2 Complex Systems Winter School

A Complex Systems Winter School took place for the first time January 12–24, 1992. Like the Summer School, this program is intended to provide graduate students and postdoctoral scientists with an intensive introduction to complex systems research, although this effort is much more narrowly focused than the month-long summer program. Courses considered an issue central to complex systems research: the geometrical and dynamical behavior of scaling complex systems. Topics covered included turbulence, percolation, self-organized criticality, $1/f$ noise, the mathematics of hierarchical systems (emphasizing fractals), fractal graphics, and scaling structures in physiology, in galaxies, and elsewhere. The school, held in Tucson, Arizona, was led by Peter Carruthers, head of the Physics Department at the University of Arizona. Sponsors were the Santa Fe Institute, the Center for Nonlinear Studies at Los Alamos National Laboratory, and the Center for Complex Systems Studies at the University of Arizona.

In 1992 DOE also allocated funds to SFI for support of a second Complex Systems Winter School. The intended theme for the School was "Dynamics of Conflict." However, we were unable to secure a broad enough faculty roster to cover all aspects of the topic and, therefore, we elected not to hold the School in Winter, 1993.

11.3 Residential Programs

The Institute's research is dominated not only by a multidisciplinary, but also a multigenerational approach. A number of young scientists, part of the increasing number attracted to complexity science, were in residence during 1992. As these researchers complete their work at SFI and move on in their academic careers, they carry the power of the complex systems approach to other organizations.

11.3.1 Postdoctoral Research

The work of the Institute's postdoctoral fellows comprises an important part of the Institute's research agenda. Occasionally the Institute also hosts shorter research visits from postdoctoral fellows with appointments at other institutions. Santa Fe Institute 1992 Postdoctoral Fellows were Walter Fontana, Tom Kepler, Cris Moore, Mats Nordahl, Paul Stolorz, and David Wolpert. Postdoctoral Fellows supported by specific SFI research programs were Bette Korber, Bill Macready, Avidan Neumann, Milan Palus, and James Theiler. The 1992 work of these researchers has been described in detail elsewhere in this report.

SFI's Postdoctoral Fellows program has been in place since 1988 and to date has involved eight full-time SFI Postdoctoral Fellows. It is highly competitive, with more than 200 applicants competing annually for one or two positions. Candidates must have or expect to receive soon a Ph.D. and should have backgrounds in theoretical physics or chemistry, computer science, mathematics, economics, game theory, theoretical biology, dynamical systems theory, or related fields. An interest in interdisciplinary research is essential.

Applicants submit a curriculum vitae, list of publications, and statement of research interests, and arrange for three letters of recommendation. Postdoctoral fellows must be sponsored by a member of the Science Board or a member of the External Faculty who agrees to take responsibility for oversight of the research of the fellow. Postdoctoral fellows are, however, free to pursue their own research interests. They are encouraged to attend workshops and to take an active part in any of the research programs of the Institute.

11.3.2 Graduate Students

Another important aspect of SFI educational activities is providing research opportunities in the sciences of complexity for graduate students. Students who have completed course work for their doctoral degree may, with the agreement of their home institutions, conduct thesis research and writing in residence at SFI under the direction of a Member of the SFI. Their degrees are granted by their home institutions. Less frequently, students at the pre-thesis graduate level conduct research at SFI. To date the Institute has hosted nearly two dozen such students; in 1992 eight graduate researchers were in residence on either a full- or part-time basis. They were Eric Chopin, Michael Diehl, Valerie Gremillion, Brant Hinrichs, Ron Hightower, Peter Hraber, Terry Jones, Avi Bergman, and Dan Pirone. The work of each is described elsewhere in this report.

11.3.3 Undergraduates

In 1989 the Institute began a small internship program for students at the undergraduate level. A testament to the Institute's estimate of the importance and commitment to this internship program is the fact that it is supported in part by a fund resulting from personal donations by SFI Science Board members. As part of this effort the Institute has brought a limited number of students to work on SFI programs or to participate in a reading and study program under the guidance of a visiting faculty member, postdoctoral fellow, or external faculty member. In 1992 these students were Randall Rose and Joshua Smith.

The Santa Fe Institute has recently been designated by the National Science Foundation as a Research Experiences for Undergraduates site. In 1993 the Institute expects to host five to seven undergraduate interns as part of this program.

11.4 Campus Relations

The Institute is synergistic rather than competitive with the great research universities, and it is currently striving to build mutually advantageous programs with them.

The relationship between SFI and the University of Michigan has established a highly successful precedent. In the past year, eight Michigan faculty spent time in residence at SFI, joining collaborations with new colleagues from other institutions, and in one or two cases even initiating collaborations among themselves that had not been feasible at home. While no other SFI-university relationships approach that one in size, there are growing clusters of SFI-influenced research at the Universities of Arizona, California at Berkeley, Chicago, Illinois, Minnesota, New Mexico, Pennsylvania, and Southern California; California Institute of Technology; Duke University; George Mason University; Stanford University; Rutgers University; and Yale University.

SFI can also claim some parentage for two new Complex Systems Centers at universities—one at the University of Arizona and one at Duke University.

In May the newly founded Krasnow Institute for Advanced Study will hold a founding workshop on "The Mind, the Brain, and Complex Adaptive Systems" featuring presentations by several SFI associates. We are hopeful that the Krasnow Institute will grow into another such Complex Systems center.

With the SFI visiting researchers program and the Summer School now having been run for five years, we're beginning to see young alumni infusing those new ideas into work at other institutions. A few examples are Stephanie Forrest (U. New Mexico), John Miller (Carnegie-Mellon), Aviv Bergman (Stanford), Julie Pullen (U. Arizona), Clare Conglon (U. Michigan), Bill Bruno (LANL), Wentian Li (Cold Spring Harbor Laboratory), Andreas Weigand (Xerox PARC), and Neil Gershenfeld (MIT). Likewise, SFI has been able to use the lure of teaching at the Schools to immerse some outstanding senior scientists in this kind of work, and they, too, are reflecting that approach in work they do at home (such as Joe Traub (Columbia), Peter Wolynes, and Jay Mittenthal (both at U. Illinois)).

Finally, several of SFI's visiting scientists have now introduced formal courses on complexity and complex adaptive systems at their home universities and elsewhere. These include Murray Gell-Mann (Caltech), Harry Swinney (U. Texas), David Campbell (U. New Mexico and U. Illinois), John Miller (Carnegie-Mellon), Peter Carruthers (U. Arizona), David Lane (U. Minnesota), and John Holland (U. Michigan).

11.5 Book Series

The purpose of SFI workshops is to stimulate new scholarship in the sciences of complexity. Appendix II lists the papers by the SFI research family that have appeared in the scientific literature. For its part, to make these results broadly available, the Institute has a multi-year agreement with Addison-Wesley for the publication of the Santa Fe Institute Studies in the Sciences of Complexity series. To assure that the cost of SFI books is reasonable and that timely material is published quickly, the publication agreement provides for the Institute to produce camera-ready copy and for the publisher to market the volumes rapidly at an affordable price. Typical prices are less than $60 for hardback and less than $30 for paperback books. In addition, most SFI research is available in preprint form before publication in the scientific literature.

The 21 books published to date are:

1987:

Emerging Syntheses in Science, edited by David Pines, Proceedings Vol. I [first proceedings volume]

1988:

Theoretical Immunology, Part One, edited by Alan S. Perelson, Proceedings Vol. II

Theoretical Immunology, Part Two, edited by Alan S. Perelson, Proceedings Vol. III

The Economy as an Evolving Complex System, edited by Philip W. Anderson, Kenneth Arrow, and David Pines, Proceedings Vol. V

Artificial Life, edited by Christopher G. Langton, Proceedings Vol. VI [first use of color]

1989:

Lattice Gas Methods for Partial Differential Equations, edited by Gary Doolen et al., Proceedings Vol. IV

Computers and DNA, edited by George I. Bell and Thomas G. Marr, Proceedings Vol. VII

Lectures in the Sciences of Complexity, edited by Daniel L. Stein, Lectures Vol. I [first lectures volume]

1990:

Complexity, Entropy, and the Physics of Information, edited by Wojciech H. Zurek, Proceedings Vol. VIII

Molecular Evolution on Rugged Landscapes: Proteins, RNA and the Immune System, edited by Alan S. Perelson and Stuart A. Kauffman, Proceedings Vol. IX

1989 Lectures in Complex Systems, edited by Erica Jen, Lectures Vol. II

Introduction to the Theory of Neural Computation, by John Hertz, Richard Palmer, and Anders Krogh, Lecture Notes Vol. I [first lecture notes volume]

Complex Systems Dynamics, by Gérard Weisbuch, Lecture Notes Vol. II [first translation]

1991:

Artificial Life II, proceedings and video, edited by Christopher G. Langton et al., Proceedings Vol. X [first videotape]

Nonlinear Modeling and Forecasting, edited by Martin Casdagli and Stephen Eubank, Proceedings Vol. XII

1990 Lectures in Complex Systems, edited by Daniel L. Stein and Lynn Nadel, Lectures Vol. III

1992:

Evolution of Human Languages, edited by Jack Hawkins and Murray Gell-Mann, Proceedings Vol. XI

Principles of Organization in Organisms, edited by Arthur Baskin and Jay Mittenthal, Proceedings Vol. XIII

The Global Dynamics of Cellular Automata: An Atlas of Basin of Attraction Fields of One-Dimensional Cellular Automata, by Andy Wuensche and Mike Lesser, Reference Volume I [first reference volume and first volume with software]

1991 Lectures in Complex Systems, edited by Daniel L. Stein and Lynn Nadel, Lectures Volume IV

Double Auction Markets, edited by John Rust, Daniel Friedman, and John Geanakoplos, Proceedings Vol. XV

Projected volumes during 1993 are:

Thinking about Biology, proceedings of the Waddington Meeting held at SFI in 1991, edited by Francisco Varela and Wilfred Stein, Lecture Notes Volume III

Artificial Life III, edited by Christopher Langton, Proceedings Vol. XVI

Audification: The Proceedings of ICAD '92, the International Conference on Auditory Display, edited by Gregory Kramer, Proceedings Vol. XVII

Predicting the Future and Understanding the Past, edited by Andreas Weigend and Neil Gershenfeld, Proceedings Vol. XVIII

1992 Lectures in Complex Systems, edited by Lynn Nadel and Daniel Stein, Lectures Volume V

Integrative Themes (title tentative), edited by George Cowan, David Pines, and David Melzer, Proceedings Vol. XIX

Understanding Complexity in the Prehistoric Southwest, edited by George Gumerman and Murray Gell-Mann, Proceedings Vol. XX

11.6 Public Education and Outreach

11.6.1 Public Lectures

The Santa Fe Institute recognizes an obligation to communicate to the general public an understanding of the newly emerging sciences of complexity. As part of this effort it hosts a regular series of popular lectures. The lectures are held monthly on the campus of St. John's College and are widely advertised in the community by posters, mailings, newspaper, and radio. They have been well received in the community and are well attended. A complete list of 1992 lecture titles and speakers appears in Appendix VII.

11.6.2 Secondary School Program

SFI has initiated a lecture/seminar program for Santa Fe's secondary school students designed to introduce them to the sciences of complexity as articulated by some of the leading researchers in the field. This two-part program combines in-school lectures by the Institute's research staff with a seminar program planned for a more limited number of students. Researchers make on-campus presentations in tandem with more in-depth seminar-discussion presentations addressed to gifted secondary school students. Criteria for student selection, program formats, and evaluation processes have been determined in consultation with local secondary school faculty, who also act as program coordinators.

12. RESEARCH ENVIRONMENT

12.1 Office Facilities

The Santa Fe Institute occupies office in three buildings at 1660 Old Pecos Trail, Santa Fe, New Mexico. This leased facility provides approximately 11,000 square feet of space, including several small seminar rooms, a conference meeting room seating up to 60, administrative offices for a staff of 15, computer facilities, limited library space, and shared office space for up to 30 scientists.

12.2 Computing Facilities

At the end of 1991, SFI's system had 21 workstations (primarily Sun, but also NeXT and Silicon Graphics) running UNIX. In 1992 the computing system had several hardware additions: Gateway 386 and 486 IBM compatibles in January, a color Sun IPX in February, a Macintosh LC 4/40 and Macintosh IIci in February, two color Decstation 5000/125s in April, two color Sun IPXs in November, and a color Sun Sparcstation10 in December. The old cisco router was replaced with an IGSr that is capable of handling increased network bandwidth for future expansion. Two 2.0-gigabyte disks were put in the Decstations for additional UNIX storage. Two HP Laserjet postscript printers were donated to the Institute. By the end of 1992 the Institute had a total of six laser printers on the network. Many Sun workstations were upgraded from 8 megabytes of RAM to 24 megabytes. A 5-gigabyte Exabyte 8500 tape drive was purchased to help relieve the load of continuous backups on the 2.3-gigabyte Exabyte 8200 tape drive. For the Suns, the operating system's release levels vary, pending software maintenance and upgrading. These hardware and software upgrades and additions were supported by a variety of funding sources and donations.

Interconnectivity plays an important role at the Institute. As much of the research supported by the Institute is conducted by teams of researchers spread around the globe and visitors with diverse computation and communications needs, the ability to communicate with distant computational resources is crucial to the success of these endeavors. This is particularly important for those needing access to supercomputing resources, which the Institute could not hope to provide at the present time. A 56-kb link to New Mexico TechNet provides the SFI's connection to NSFNet and thereby to the worldwide Internet. Additionally, the ability of the staff to communicate work in progress quickly and efficiently with one another, as well as to share hardware and software resources, has aided greatly with the day-to-day operation of the Institute. Local connectivity is provided by Ethernet and Appletalk local area networks.

Effort has also been devoted to the development of software resources at the Institute. The availability of programming environments, programming languages, text-processing systems, and advanced graphics-rendering utilities is vital to the computer-bound research programs supported by the Institute. A variety of software is now installed and supported on the Suns including, among others, the NeWS window system (OpenWindows), the Kermit communications package, numerous graphics systems, C, C++, Lisp, and Fortran compilers, the Mathematica symbolic mathematical package, name server software, LaserWriter software, Mac-Ethernet connection software, the EMACS editor, the XII window system, NCSA's Imagetool system, and a TEX text-processing system.

12.3 Library Resources

The Institute is slowly building its library resources through purchases and as the recipient of several donated collections. SFI houses approximately 1,500 volumes as part of the Stanislas Ulam Collection and holds volumes of *The Physical Review*, 1944–1989, as part of the Herbert L. Anderson Collection. In 1990 the Institute received more than 2,000 volumes, principally in mathematics and physics, from the library of the late Paul R. Stein. In 1990 the Addison-Wesley Collection was also established with a initial donation of 30 titles in the Addison-Wesley Advanced Book Program.

SFI maintains a growing (p)reprint collection of relevant literature in the sciences of complexity. Among our seventeen current journal subscriptions are *Complex Systems*, *Nature*, *Neural Computation*, and *Science*. Library facilities are supplemented by an interlibrary loan arrangement with nearby Los Alamos National Laboratory and the University of New Mexico.

SFI WORKING PAPERS (JANUARY 1992 TO APRIL 1993)

92-01-001 "Persistence of the Dow Jones Index on Rising Volume"
Blake LeBaron

92-01-002 "Mathematical Approaches in Immunology"
Alan S. Perelson

92-01-003 "Maxwell's Demon, Rectifiers, and the Second Law: Computer Simulation of Smoluchowski's Trapdoor"
P. A. Skordos and W. H. Zurek

92-01-004 "Growth and Recruitment in the Immune Network"
Rob J. De Boer, Pauline Hogeweg, and Alan S. Perelson

92-01-005 "The Dynamics of HIV Infection of $CD4^+$ T Cells"
Alan S. Perelson, Denise E. Kirschner, George W. Nelson, and Rob De Boer

92-01-006 "On the Connection Between [illegible]-Sample Testing and Generalization Error"
David H. Wolpert

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Walter Fontana, Danielle A. M. Konings, Peter F. Stadler, and Peter Schuster

92-02-008 "Behavior of Trading Automata in a Computerized Double Auction Market"
John Rust, Richard Palmer, and John H. Miller

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H. Peyton Young

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Martin Shubik

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Paul Stolorz

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David H. Wolpert and Paul Stolorz

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David H. Wolpert

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John F. Gibson, J. Doyne Farmer, Martin Casdagli, and Stephen Eubank

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Ioannis Karatzas, Martin Shubik, and William D. Sudderth

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Rob J. De Boer, Ioannis G. Kevrekidis, and Alan S. Perelson

92-05-024 "Immune Network Behavior II: From Oscillations to Chaos and Stationary States"
Rob J. De Boer, Ioannis G. Kevrekidis, and Alan S. Perelson

92-06-025 "Development of the T-cell Repertoire: Clone Size Distribution"
Stephen J. Merrill, Rob J. De Boer, and Alan S. Perelson

92-06-026 "Steady State Flux-Flux Correlation Functions for Elementary Processes"
Joel Keizer

92-06-027 "Searching for Diverse, Cooperative Populations with Genetic Algorithms"
Robert E. Smith, Stephanie Forrest, and Alan S. Perelson

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John R. Koza, James P. Rice, and Jonathan Roughgarden

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Stephanie Forrest and Melanie Mitchell

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Bernhard Sulzer, Avidan U. Neumann, J. Leo van Hemmen, and Ulrich Behn

93-03-016 "On Overfitting Avoidance as Bias"
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LIST OF 1992 COLLOQUIA

The Quantum Mechanics of History
Jonathan Halliwell, Massachusetts Institute of Technology

Wavelets and Spatio-Temporal Chaos
Gottfried Mayer-Kress, University of Illinois, Urbana-Champaign

A Global Approach to Science Education
Joel de Rosnay, Cité des Sciences et de l'Industrie, Paris

Modes of Thought in Law: Pueblo Tribal Court Studies in Cultural Complexity
Wolfgang Fikentscher, University of Munich

Nasty Analysis of Simple Phenomena and Simple Analysis of Complex Phenomena
Stephen Pollock, University of Michigan

Quantum Mechanical Systems as Universal Simulators
Seth Lloyd, Los Alamos National Laboratory .

An Overview of the Adaptive Computation Program at SFI
Melanie Mitchell, University of Michigan

Braids in Classical Gravity
Cris Moore, Santa Fe Institute

The Theory and History of Money and Financial Institutions: An Overview
Martin Shubik, Yale University

Information Theoretical Methods to Characterize the Temporal and Spatial Organization in Complex Networks
Claudia Pahl-Wostl, Swiss Federal Institute of Technology

Recursive Definition of Global Cellular Automata Mappings and Some Applications of These Mappings
Steen Rasmussen, Los Alamos National Laboratory/Santa Fe Institute

Current Research on Computational Models of the Immune System
Stephanie Forrest, University of New Mexico

Finite-Dimensional Systems Capable of Universal Computation
Cris Moore, Santa Fe Institute

Bifurcation Structure of Periodically Driven Nonlinear Oscillators
Ulrich Parlitz, University of Darmstadt

Nanobiology—Exploiting Nanoscale Mechanisms in Living Systems
Stuart Hameroff, University of Arizona

Money is Funny, or Why Finance is Too Complex for Physics
John Casti, Santa Fe Institute

Molecular Turing Structures in the Biochemistry of the Cell
Brosl Hasslacher, Los Alamos National Laboratory

Polymers, Adsorption and Vicious Walkers
Turab Lookman, University of Western Ontario

Map Studies of Replicator Dynamics
Paul Phillipson, University of Colorado

Information and Returns to Scale
Kenneth Arrow, Stanford University

The Ghost in the Machine: Basin of Attraction Fields of Disordered Cellular Automata Networks
Andrew Wuensche, London

Controls and "Impacts" on Multiple-Attractor Systems
E. Atlee Jackson, University of Illinois, Urbana-Champaign

Dynamical Systems: Transdisciplinary Mathematical Tool or Fiction?
Ivan Dvorak, Prague Psychiatric Center

Concurrent Local Dynamics in Elementary Cellular Automata
Guangzhou Zou, Texas A&M University

Generalization in Boolean and Neural Networks
Chris Van Den Broeck, University of California, San Diego, and NFWO-Belgium

Two Roles for Calcium in Agonist Stimulated Calcium Oscillations in Living Cells
Joel Keizer, University of California, Davis

Genome Regulation in Mammalian Cells: Applications to Biology and Medicine
Theodore Puck, Eleanor Roosevelt Institute

Three Lectures on the Theory of Money and Financial Institutions
Martin Shubik, Yale University

Probabilities in Computing
Wray Buntine, NASA

Inference of Physical Phenomena: Abstract Tomography, Gedanken Experiments, and Surprisal Analysis
Charlie Strauss, Los Alamos National Laboratory

Chaos and Hyperchaos in Human Decision-Making Behavior
Erik Mosekilde, Technical University of Denmark

Quantum Statistical Inference
Richard Silver, Los Alamos National Laboratory

Two Applications of De Bruijn Digraphs to Automata Theory
Niall Graham, Los Alamos National Laboratory

Mutual Information and Nonlinear Neural Oscillations
H.G. Schuster, University of Kiel

Root Insertion, Cartesian Trees, and Dynamics Memory Allocation
C.J. Stephenson, IBM Research

Emergence, Hierarchies and Hyperstructures
Nils Baas, University of Trondheim

Fitness and Adaptation of Digital Organisms
Walter Tackett, Hughes Aircraft/University of Southern California

The Second Metamorphosis of Science
E. Atlee Jackson, University of Illinois, Urbana-Champaign

Qualitative Computing
Françoise Chatelin, University of Paris IX and Thomson—CSF

Life as a Manifestation of the Second Law of Thermodynamics
Eric Schneider, National Oceanic and Atmospheric Administration

Synthetic Nanostructures as Control Systems
Günter Mahler, University of Stüttgart

Information and Entropy. I. How Complex are Physical States?
Information and Entropy. II. Can Dynamics Access Complex Physical States?
Carlton Caves, University of New Mexico/Santa Fe Institute

Olfaction: From Models of Molecular Recognition to Genetic Diversity and Neuronal Processing
Doron Lancet, Weizmann Institute of Science

Information-Theoretic Incompleteness
Gregory Chaitin, IBM Research, Yorktown Heights

Algebraic Cellular Automata and Efficient Prediction Algorithms
Cris Moore, Santa Fe Institute

Stigmergic Swarms, and Stigmergic Process Gasses
Mark Millonas, Los Alamos National Laboratory

Multidimensional Pattern Formation has an Infinite Number of Constants of Motion
Mark Mineev-Weinstein, Courant Institute/Los Alamos National Laboratory

The Shape Space of RNA
Ivo Hofacker, University of Vienna

Culture as a Complex Adaptive System: A Discourse for Friday the Thirteenth
George Gumerman, Southern Illinois University at Carbondale

Simple Solvent-Driven Models of Protein Folding
Paul Stolorz, Santa Fe Institute

Maturation Windows and Early Mental Development in Children
Bela Julesz, California Institute of Technology and Rutgers, and
George Cowan, Los Alamos National Laboratory and Santa Fe Institute

Memory Systems, Computation and the Second Law
David Wolpert, Santa Fe Institute

Resource Flows in Artificial Ecologies
Mats Nordahl, Santa Fe Institute

Modeling Studies of Somatic Hypermutation in B Cells
Tom Kepler, Santa Fe Institute

Punctuated Inductions and Software Arms Races
Jordan Pollack, Ohio State University

Remarks on the Concept of Meaning in the Exact Sciences
Harald Atmanspacher, Max Planck Institute, Garching

Automatic Programming of Sorting Networks: A Comparison Between Genetic Algorithms and Traditional Search Techniques
Bill Laaser, Interval Research Corp.

Symmetric Chaos: What Is It and How Do We Detect It?
Greg King, University of Warwick

Detecting Nonlinearity in Magnetospheric Activity
Dean Prichard, University of Alaska, Fairbanks

LIST OF 1992 WORKSHOPS

January 12–24	1991 Complex Systems Winter School (Held in Tucson, Arizona) *Peter Carruthers, University of Arizona*
February 19–22	Working Group on Theory of Money and Financial Institutions *Martin Shubik, Yale University*
February 20–23	Adaptive Processes and Organization *Michael Cohen, University of Michigan* *David Lane, University of Minnesota*
February 25–29	Resource Stress and Response in the Prehistoric Southwest *Joseph Tainter, U.S. Forest Service*
March 10–15	Founding Workshop in Adaptive Computation *John Holland, University of Michigan* *John Miller, Carnegie-Mellon University* *Adaptive Computation Directorate*
March 20–22	Increasing Returns *Martin Shubik, Yale University*
April 16–19	Theoretical Computation in the Social Sciences *Michele Boldrin, Northwestern University* *John Miller, Carnegie-Mellon University*
April 24–26	Biology and Economics: Overlapping Generations *Martin Shubik, Yale University*
May 1–4	Working Group on Theory of Money and Financial Institutions *Martin Shubik, Yale University*
May 14–17	NATO Advanced Research Workshop on Comparative Time Series Analysis *Neil Gershenfeld, Harvard University* *Andreas Weigend, Xerox Palo Alto Research Center*
May 24–26	What OR Models have to Offer CAS, and Vice Versa *John Holland, University of Michigan* *Stephen Pollock, University of Michigan*
May 31–June 26	1992 Complex Systems Summer School *Lynn Nadel, University of Arizona* *Daniel Stein, University of Arizona*
June 15–19	Artificial Life III *Christopher Langton, Los Alamos National Laboratory*
July 8–15	Integrative Workshop: Common Principles of Complex Systems *George Cowan, Santa Fe Institute*
August 6–7	The Future of Supervised Machine Learning *David Wolpert, Los Alamos National Laboratory and Santa Fe Institute*
October 28–30	Audification Workshop *Gregory Kramer, Clarity*
November 6–9	Approaches to Artificial Intelligence *Nils Nilsson, Stanford University* *David Rumelhart, Stanford University*

November 16–20 **Working Group on Computation, Dynamical Systems, and Learning**

Melanie Mitchell, University of Michigan and Santa Fe Institute

LIST OF 1992 VISITORS

Harald Atmanspacher	Max Planck Institute, Garching
Charles Anderson	Jet Propulsion Laboratory
Kenneth Arrow	Stanford University
Brian Arthur	Stanford University
Joseph Atick	Institute for Advanced Study
Nils Baas	University of Trondheim
Wyeth Baer	California Institute of Technology
Per Bak	Brookhaven National Laboratory
Denis Baylor	Stanford University Medical School
Aviv Bergman	Interval Research Corporation
William Bialek	NEC Research Institute
John Casti	Technical University of Vienna
Carlton Caves	University of New Mexico
Françoise Chatelin	University of Paris IX/Thomson–CSF
Eric Chopin	Ecole Normale Supérieure de Lyons
Hirsch Cohen	Sloan Foundation
Jim Crutchfield	University of California, Berkeley
Rob de Boer	University of Utrecht
Gary de Young	University of California, Davis
Michael Diehl	State University of New York at Buffalo
Guillemette Duchateau	Ecole Normale Supérieure, Paris
Ivan Dvorak	Prague Psychiatric Center
Wolfgang Fikenstscher	University of Munich
Murray Gell-Mann	California Institute of Technology
Charles Gilbert	Rockefeller University
Brian Goodwin	Open University
Jean-Michel Grandmont	CEPREMAP, Paris
Jim Hanson	University of California, Berkeley
Peter Heilbrun	University of Utah
David Hiebeler	Thinking Machines Corporation
Stefan Helmreich	Stanford University
Brant Hinrichs	University of Illinois, Urbana-Champaign
Ivo Hofacker	University of Vienna
John Holland	University of Michigan
Alfred Hubler	University of Illinois
E. Atlee Jackson	University of Illinois
Terry Jones	University of Indiana
Stuart Kauffman	University of Pennsylvania
Joel Keizer	University of California, Davis
Christof Koch	California Institute of Technology
Tim Kohler	Washington State University
Hidetoshi Konno	University of Tsukuba
Greg Kramer	Clarity
Blake LeBaron	University of Wisconsin
Michael Lewicki	California Institute of Technology
Ralph Lewis	Dartmouth University
Zhaoping Li	Institute for Advanced Study
Kristian Lindgren	Chalmers Institute of Technology
André Longtin	University of Ottawa
Carlo Lucheroni	Universita Delgi Studi di Perugia

David Mackay	Cambridge University
Bill Macready	Canada
Günter Mahler	University of Stüttgart
Gottfried Mayer-Kress	University of Illinois, Urbana-Champaign
Marcus Meister	Harvard University
Birgit Merté	Technical University of Munich
John Miller	Carnegie-Mellon University
Kenneth Miller	California Institute of Technology
Melanie Mitchell	University of Michigan
Harold Morowitz	George Mason University
Avidan Neumann	Weizmann Institute
Steve Omohundro	University of California, Berkeley
Richard Palmer	Duke University
Milan Palus	Prague Psychiatric Center
Ulrich Parlitz	University of Darmstadt
Klaus Pawelzik	University of Frankfurt
Paul Phillipson	University of Colorado
David Pines	University of Illinois, Urbana-Champaign
Dan Pirone	University of Washington
Jordan Pollock	Ohio State University
Stephen Pollock	University of Michigan
Rama Ranganathan	University of California, San Diego
Tom Ray	University of Delaware
Luis Reyna	IBM T. J. Watson Research Center
R. Clay Ried	Rockefeller University
Neantro Saavedra-Rivano	University of Tsukuba
H. G. Schuster	University of Kiel
Peter Schuster	Institut für Molekulare Biotechnologie, Jena
Terrence Sejnowski	The Salk Institute
Martin Shubik	Yale University
Joshua Smith	Cambridge University
Matthew Sobel	State University of New York at Stony Brook
Peter Stadler	University of Vienna
Chris Stephenson	IBM Research, Yorktown Heights
Charles Stevens	The Salk Institute
Michael Stryker	University of California Medical School
William Sudderth	University of Minnesota
Walter Tackett	Hughes Aircraft/University of Southern California
Kurt Thearling	Thinking Machines Corporation
Guy Theraulaz	CNRS, Marseille
David Van Essen	California Institute of Technology
Gérard Weisbuch	Ecole Normale Supérieure, Paris
Andy Wuensche	Santa Fe Institute
Udi Zohary	Stanford University Medical School

ROSTERS & SCHEDULES OF WORKSHOPS

Roster for the 1991 Complex Systems Winter School, January 12–24, 1992

Faculty

Prof. Philip Anderson	Princeton University
Prof. Hendrick Bohr	University of Illinois, Urbana
Prof. David Campbell	University of Illinois, Urbana
Prof. Mitchell Feigenbaum	Rockefeller University
Prof. Michael Fisher	University of Maryland at College Park
Prof. Murray Gell-Mann	California Institute of Technology
Prof. Larry Gray	University of Minnesota
Dr. Rajan Gupta	Los Alamos National Laboratory
Dr. Erica Jen	Los Alamos National Laboratory
Prof. David Levermore	University of Arizona
Dr. Paul Meakin	E.I. du Pont de Nemours & Company
Prof. Yves Pomeau	University of Arizona
Dr. Chao Tang	NEC Research Institute
Prof. Bruce West	University of North Texas
Dr. Geoffrey West	Los Alamos National Laboratory
Prof. Vladimir Zakharov	University of Arizona

Students

Robert Axtell	Carnegie-Mellon University
Ofer Biham	Syracuse University
Luca Cortelezzi	California Institute of Technology
Diego del-Castillo-Negrete	University of Texas at Austin
Kresimir Demeterfi	Brown University
Ricardo Garcia-Pelayo	University of Texas at Austin
Sandip Goshal	Stanford University
Andrea Giasanti	University of Rome
Dimitry Gupalo	Rockefeller University
Charles Hanna	IBM T.J. Watson Research Center
Alfred Hanssen	University of Tromso/Los Alamos National Laboratory
Igor Herbut	John Hopkins University
Andreas Herz	California Institute of Technology
Terrence Hwa	Harvard University
Mathieu Kemp	University of North Carolina
Ronnie Manieri	Los Alamos National Laboratory
Jose Luis Mateos	Universite Nacional Autonoma de México
Robert McCann	Princeton University
Patrick McGuire	University of Arizona
William Miller	Brooks Air Force Base
Mark Millonas	University of Texas at Austin
Balasubramanya Nadiga	California Institute of Technology
Onuttom Narayan	Harvard University
Julie Pullen	University of Arizona
Wouter-Jan Rappel	Ecole Normale Supérieure
Sarah Schofield	University of Illinois, Urbana
Troy Shinbrot	University of Maryland

Nicholas Tufillaro	Woods Hole Oceanographic Institute
Jane Wang	Los Alamos National Laboratory
Erik Winfree	Wolfram Research/California Institute of Technology

Program for the 1991 Complex Systems Winter School, January 12–24, 1992

SUNDAY JANUARY 12

5:00–6:30 P.M.	Opening Talk: Fun with Size and Scale; Ranging from Elephants and Quarks to the Early Universe. Geoffrey West

MONDAY JANUARY 13

9:00–10:30 A.M.	Nonlinear Science: From Paradigms to Practicalities I. David Campbell
11:00 A.M. –12:30 P.M.	Scaling and Correlations in Critical Phenomena I. Michael E. Fisher
2:00–3:30 P.M.	Introduction to Cellular Automata. Erica Jen

TUESDAY JANUARY 14,

9:0010:30 A.M.	Nonlinear Science: From Paradigms to Practicalities II. David Campbell
11:00 A.M. –12:30 P.M.	Scaling and Correlations in Critical Phenomena II. Michael E. Fisher
2:00–3:30	Scaling in Linear Cellular Automata. Erica Jen
2:00–3:30	Introduction to Lattice Gases. C. David Levermore

WEDNESDAY JANUARY 15

8:00–9:00 A.M.	*Breakfast served*
9:00–10:30	Tunable Fractals, Scaling and Nonfractals in Planar Vesicles. Michael E. Fisher
10:30–11:00	*Break*
11:00 A.M. –12:30 P.M.	Scaling and the Renormalization Group in Particle Physics. Geoffrey West
2:00 –3:30	To be announced Rajan Gupta
4:00–5:15	Colloquium at University of Arizona Philip Anderson

THURSDAY JANUARY 16

8:00–9:00 A.M.	*Breakfast served*
9:00–10:30	Fractal Physiology and Chaos in Medicine I. Bruce West
10:30–11:00	*Break*
11:00 A.M.–12:30 P.M.	Exactly Solvable 1-D Cellular Automata. Erica Jen

12:30–2:00	*Lunch*
2:00–3:30	Relationships Between Localization, Spin Glasses, and Avalanche Models Generalities in Self-Organized Critical Behaviors. Philip W. Anderson
4:00–5:30	Zipf's Law and Related Mysteries. Murray Gell-Mann

FRIDAY JANUARY 17

8:00–9:00 A.M.	*Breakfast served*
9:00–10:30	Fractal Physiology and Chaos in Medicine II. Bruce West
10:30–11:00	*Break*
11:00 A.M. –12:30 P.M.	Discrete Kinetic Theories. C. David Levermore
12:30–2:00	*Lunch*
7:00	*Banquet* Nature Conformable to Herself. Murray Gell-Mann Remarks: Henry Koffler, Former University of Arizona President

SATURDAY JANUARY 18

8:00–9:00 A.M.	*Breakfast served*
9:00–10:30	Fractal Physiology and Chaos in Medicine III. Bruce West
11:00 A.M. –12:30 P.M.	Lattice Kinetic Theories. C. David Levermore

MONDAY JANUARY 20

8:00–9:00 A.M.	*Breakfast served*
9:00–10:30	Application of Fractals and Scaling I. Paul Meakin
10:30–11:00	*Break*
11:00 A.M. –12:30 P.M.	To be announced Larry Gray
12:30–2:00	*Lunch*
2:00–3:30	From Nonlinear Schrödinger to Complex Ginsberg-Landau Equations I. Yves Pomeau

TUESDAY JANUARY 21

8:00–9:00 A.M.	*Breakfast served*
9:00–10:30	Applications of Fractals and Scaling II. Paul Meakin
10:30–11:00	*Break*
11:00 A.M.–12:30 P.M.	To be announced Larry Gray
12:30–2:00	*Lunch*

2:00–3:30	From Nonlinear Schrödinger to Complex Ginsberg-Landau Equations II. Yves Pomeau

WEDNESDAY JANUARY 22

8:00–9:00 A.M.	*Breakfast served*
9:00–10:30	Applications of Fractals and Scaling III. Paul Meakin
10:30–11:00	*Break*
11:00 A.M. –12:30 P.M.	To be announced Larry Gray
12:30–2:00	*Lunch*
4:00–5:15	Colloquium at the University of Arizona Mitchell Feigenbaum

THURSDAY JANUARY 23

8:00–9:00 A.M.	*Breakfast served*
9:00–10:30	Self-Organized Critical Phenomena from Sandpiles to Earthquakes I. Chao Tang
10:30–11:00	*Break*
11:00 A.M. –12:30 P.M.	To be announced Vladimir Zakharov
12:30–2:00	*Lunch*
2:00–3:30	Scaling Theory of One-Dimensional Maps I. Mitchell Feigenbaum

FRIDAY JANUARY 24

8:00–9:00 A.M.	*Breakfast served*
9:00–10:30	Self-Organized Critical Phenomena from Sandpiles to Earthquakes II. Chao Tang
10:30–11:00	*Break*
11:00 A.M. –12:30 P.M.	To be announced Vladimir Zakharov
12:30–2:00	*Lunch*
2:00–3:30	Scaling Theory of One-Dimensional Maps II. Mitchell Feigenbaum

Roster for the Working Group Meeting on the Theory of Money and Financial Institutions, February 18–22, 1992

Prof. Robert Anderson	University of California, Berkeley
Prof. Pradeep Dubey	State University of New York
Mr. A. Krishna Jayawardene	Yale University
Prof. Ioannis Karatzas	Columbia University
Prof. S. Sahi	Princeton University
Prof. Lloyd Shapely	University of California, Los Angeles
Prof. Martin Shubik	Cowles Foundation
Prof. William Sudderth	University of Minnesota
Dr. Dimitri Tsomocos	Yale University

Program for the Working Group Meeting on the Theory of Money and Financial Institutions, February 18–22, 1992

Formal program not available.

Roster for the Workshop on Adaptive Processes and Organization, February 20–23, 1992

Prof. Robert Axelrod	University of Michigan
Prof. Leo Buss	Yale University
Prof. Michael Cohen	University of Michigan
Dr. George Cowan	Los Alamos National Laboratory
Prof. Massimo Egidi	University of Trento
Dr. Walter Fontana	Santa Fe Institute
Prof. Les Gasser	University of Southern California
Mr. Joel Getzendanner	Joyce Foundation
Prof. Larry Gray	University of Minnesota
Dr. George Gumerman	Southern Illinois University at Carbondale
Dr. W. Daniel Hillis	Thinking Machines Corp.
Prof. John Holland	University of Michigan
Dr. Stuart Kauffman	Santa Fe Institute
Prof. David Lane	University of Minnesota
Prof. Dan Levinthal	University of Pennsylvania
Prof. James March	Stanford University
Prof. John H. Miller	Carnegie-Mellon University
Prof. John Padgett	University of Chicago
Mr. James Pelkey	Santa Fe Institute
Prof. Martin Shubik	Yale University
Prof. Massimo Warglien	University of Venice Ca' Bembo
Prof. Karl Weick	University of Michigan
Dr. Gérard Weisbuch	Ecole Normale Supérieure
Dr. Sidney Winter	General Accounting Office

Program for the Workshop on Adaptive Processes and Organization, February 20–23, 1992

Note Paper sessions include 25 minutes for initial presentation, 10 minutes for discussion by author, and 25 minutes for general discussion per paper.

THURSDAY, FEBRUARY 20

8:30 A.M.	*Continental breakfast*
9:00	Welcome and Introductions
9:30	An Overview of Emerging Connections: Recent Theoretical Issues in Organization Theory and Developments in Complex Adaptive Systems Michael Cohen, Chair
11:30	*Lunch*
1:00–5:00 P.M.	First Paper Session Three papers by: James March (David Lane, presenter) Karl Weick (Les Gasser, presenter) John Holland (Sidney Winter, presenter)

FRIDAY, FEBRUARY 21

8:30 A.M.	*Continental breakfast*
9:00 A.M.–12:30 P.M.	Second Paper Session

Three papers by:
Robert Axelrod (Gérard Weisbuch, presenter)
John Padgett (Walter Fontana, presenter)
Stuart Kauffman (Dan Levinthal, presenter)

Lunch

FREE AFTERNOON

SATURDAY, FEBRUARY 22

8:30 A.M.	*Continental Breakfast*
9:00	Common Themes and Reflections Massimo Warglien, Chair
12:00 NOON	*Lunch*
1:30–4:00 P.M.	Group Discussions (Also, each participant will prepare a paragraph describing possible future directions that have emerged in the workshop.)
7:00	*Cocktails* Inn on the Alameda
8:00	*Dinner* Fabios, 227 Don Gaspar Avenue, 984-3080

SUNDAY, FEBRUARY 23

8:30 A.M.	*Continental Breakfast*
9:00	Michael Cohen, Chair Common Themes and Future Proposals
11:30	Adjourn

Roster for the Workshop on Resource Stress and Response in the Prehistoric Southwest, February 25–29, 1992

Dr. M. Pamela Bumstead	Santa Fe, New Mexico
Dr. Linda Cordell	California Academy of Science
Dr. Jeffrey Dean	University of Arizona
Prof. Marcus W. Feldman	Stanford University
Prof. Murray Gell-Mann	California Institute of Technology
Dr. George Gumerman	Southern Illinois University, Carbondale
Dr. Michelle Hegmon	New Mexico State University
Dr. Stuart Kauffman	Santa Fe Institute
Dr. Timothy Kohler	Washington State University
Dr. Chris G. Langton	Los Alamos National Laboratory
Dr. Robert Leonard	University of New Mexico
Dr. Paul Minnis	University of Oklahoma
Dr. Margaret Nelson	State University of New York
Dr. Robert W. Preucel	Harvard University
Dr. Alison Rautman	Central Michigan University
Dr. John Ravesloot	Tucson, Arizona
Dr. Katherine Spielmann	Arizona State University
Dr. Alan Sullivan	University of Cincinnati
Dr. Christine Szuter	University of Arizona Press
Dr. Joseph Tainter	USDA Forest Service

Program for the Workshop on Resource Stress and Response in the Prehistoric Southwest, February 25–29, 1992

TUESDAY, FEBRUARY 25

A.M.

Topic: Modeling

"Modeling Past Environments and Subsistence Systems"
Timothy Kohler
Moderator: Alan Sullivan

P.M.

Topic: Social and Cultural Responses

"Risk, Reciprocity, and the Operation of Social Networks"
Alison Rautman
Moderator: Michelle Hegmon

"The Integration and Evolution of Culture: Anasazi Examples"
George Gumerman
Moderator: Katherine Spielmann

WEDNESDAY, FEBRUARY 26

A.M.

Topic: Anthropogenic Environmental Changes

"Agriculture, Hunting, and Gathering: Human Responses to Anthropogenic Environmental Changes"
Christine Szuter
Moderator: Jeffrey Dean

P.M.

Topic: General Adaptive Responses

"Economic Uncertainty and Behavioral Strategies"
Paul Minnis
Moderator: Margaret Nelson

" Demography, Environment, and Subsistence Stress"
Jeffrey Dean
Moderator: George Gumerman

THURSDAY, FEBRUARY 27

A.M. Topic: Research Involving Recent Southwesterners

"Agricultural Variability, Strategies of Storing and Sharing, and the Pithouse to Pueblo Transition in the Northern Southwest"
Michelle Hegmon
Moderator: Christine Szuter

P.M. Afternoon: Free to explore Santa Fe

Evening: Banquet - time and place to be announced

7:00 P.M. Fabio's, 227 Don Gaspar Avenue (984-3080)

FRIDAY, FEBRUARY 28

A.M. Topic: Technological Change

"Change in Technological Organization as Response to Subsistence Stress"
Margaret Nelson
Moderator: Robert Leonard

P.M. Topic: Theoretical Issues

"Theoretical Aspects of Subsistence Stress and Cultural Evolution"
Robert Leonard and Alysis Abbott
Moderator: Timothy Kohler

"Foundations for Interpreting the Anasazi Archaeoeconomic Record"
Alan Sullivan
Moderator: Robert Preucel

SATURDAY, FEBRUARY 29

A.M. & P.M. Topic: Flexibility Among Agriculturalists

"Hunting and Health Among Agricultural Populations"
Katherine Spielman
Moderator: Alison Rautman

Farmers on the Move: Mobility and Settlement Among Subsistence Agriculturalists"
Robert Preucel
Moderator: Paul Minnis

Workshop will end by mid afternoon

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Roster for the Founding Workshop in Adaptive Computation, March 10–15, 1992

Prof. Richard K. Belew	University of California, San Diego
Dr. Aviv Bergman	Interval Research Corp.
Dr. Felix E. Browder	Rutgers University
Prof. Arthur W. Burks	Ann Arbor, MI
Prof. Freddy Christiansen	University of Aarhus
Dr. Tom Dietterich	Oregon State University
Ms. Esther Dyson	EDventure Holdings, Inc.
Dr. Doyne Farmer	The Prediction Company
Prof. Marcus W. Feldman	Stanford University
Prof. Stephanie Forrest	University of New Mexico
Dr. W. Daniel Hillis	Thinking Machines Corp.
Prof. John Holland	University of Michigan
Dr. Stuart Kauffman	Santa Fe Institute
Dr. Chris G. Langton	Los Alamos National Laboratory
Dr. Alan S. Lapedes	Los Alamos National Laboratory
Mr. David Liddle	Interval Research Corp.
Dr.. Nick Littlestone	NEC Research Institute
Dr. Nicholas C. Metropolis	Los Alamos National Laboratory
Prof. Melanie Mitchell	Santa Fe Institute
Dr. Jorge Muruzabal	University of Minnesota
Prof. Nils Nilsson	Stanford University
Prof. Norman Packard	Prediction Company
Prof. Richard G. Palmer	Duke University
Mr. James Pelkey	Atherton, CA
Dr. Alan Perelson	Los Alamos National Laboratory
Dr. Tom Ray	University of Delaware
Dr. Rick Riolo	University of Michigan
Prof. Jonathan Roughgarden	Stanford University
Prof. David E. Rumelhart	Stanford University
Prof. Martin Shubik	Cowles Foundation
Dr. L. M. Simmons, Jr.	Santa Fe Institute
Mr. Richard Sutton	GTE Laboratories
Dr. Will Wright	Maxis
Prof. Lev Zhivotovsky	Russian Academy of Sciences

Program for the Founding Workshop in Adaptive Computation, March 10–15, 1992

TUESDAY, MARCH 10

8:30–9:00 A.M.	*Continental Breakfast*
9:00–9:15	Introductions
9:15 A.M.–12:15 P.M.	Visions of Adaptive Computation (Issues/Examples) Series of 15 minute talks to highlight issues/examples
12:15–1:15	*Lunch*
1:15–3:15	Visions of Adaptive Computation (Cont.)
3:15–5:00	Directions and Opportunities in Adaptive Computation Moderator: John Miller

WEDNESDAY, MARCH 11

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:30	Neural Networks (Technique) Richard Palmer
10:45 A.M.–12:15 P.M.	Adaptive Computation in ECHO (Issues/Examples) John Holland
12:15–1:30	*Lunch*
1:30–3:00	Computational Learning Theory (Technique) Nick Littlestone
3:15–5:00	Directions and Opportunities in Adaptive Computation Moderator: Marc Feldman

THURSDAY, MARCH 12

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:30	Adaptive Computation in the Immune System (Issues/Examples) Alan Perelson
10:45 A.M.–12:15 P.M.	Adaptive Computation in Biology (Issues/Examples) Tom Ray
12:15–1:30	*Lunch*
1:30–3:00	Temporal Difference Methods (Technique) Rich Sutton
3:15–5:00	Directions and Opportunities in Adaptive Computation Moderator: Art Burks

FRIDAY, MARCH 13

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:15	Simulated Evolution and Punctuated Equilibrium (Issues/Examples) Danny Hillis
10:15–11:30	Genetic Algorithm/Classifier (Technique) Melanie Mitchell
11:45A.M.–1:00 P.M.	Adaptive Computation in Physical Systems (Issues/Examples) Chris Langton
	FREE AFTERNOON

SATURDAY, MARCH 14

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:30	Adaptive Computation in Robotics (Issues/Examples) Nils Nilsson
10:45 A.M. –12:15 P.M.	Symbolic Learning (Issues /Examples) Tom Dieterich
12:15–1:30	*Lunch*
1:30–3:00	Complex Data Analysis (Technique) Norman Packard
3:00–5:00	Directions and Opportunities in Adaptive Computation Moderator: Nils Nilsson
7:30	*Group Dinner*

SUNDAY, MARCH 15

8:30–9:00 A.M.	*Continental Breakfast*
9:00–12:00 NOON	Visions of Adaptive Computation Moderator: Melanie Mitchell
12:00 NOON	Adjourn

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1:30 P.M.	Adaptive Computation Directorate Meeting

Roster for the Workshop on Increasing Returns, March 20–22, 1992

Prof. Kenneth J. Arrow	Stanford University
Prof. W. Brian Arthur	Stanford University
Dr. Per Bak	Brookhaven National Laboratory
Dr. George Cowan	Los Alamos National Laboratory/Santa Fe Institute
Prof. Giovanni Dosi	University of Rome
Dr. Ralph E. Gomory	Alfred P. Sloan Foundation
Dr. Stuart Kauffman	Santa Fe Institute
Prof. Alan Kirman	European University
Prof. Paul Krugman	Massachusetts Institute of Technology
Mr. Robert Maxfield	Saratoga, California
Prof. Richard Nelson	Columbia University
Mr. James Pelkey	Santa Fe Institute
Prof. Walter Powell	University of Arizona
Prof. Herbert Scarf	Yale University
Prof. Martin Shubik	Yale University
Dr. Gerald Silverberg	University of Linburg
Prof. Robert Solow	Massachusetts Institute of Technology

Program for the Workshop on Increasing Returns, March 20–22, 1992

FRIDAY, MARCH 20, 1992

8:30–9:00 A.M.	*Continental Breakfast*
9:00–9:15	Welcome & Introductions Martin Shubik
9:15–9:45	Preliminary Remarks Kenneth Arrow
9:45–11:00	Learning and Increasing Returns Brian Arthur
11:00–11:15	*Break*
11:15 A.M.–12:30 P.M.	Strategic Pricing in Markets with Conformity Effects Andzrej Ruszczynski
12:30–1:30	*Lunch*
1:30–2:45	Endogenous Fluctuations Arising From Stochastic Encounters Among Agents Alan Kirman
2:45–4:00	Positive Feedback, the "Matthew Effect," and the Distribution of Scientific Productivity Paul David

SATURDAY, MARCH 21

8:30–9:00 A.M.	*Continental Breakfast*
9:00 –10:15	Coevolution of Technology and Institutions Richard Nelson
10:15–11:30	Dynamics of Regional Agglomeration Paul Krugman
11:30–11:45	*Break*
11:45 A.M.–1:00 P.M.	Evolutionary Nonlinear Modeling Gerald Silverberg

1:00–2:00	*Lunch*
2:00–3:15	A Ricardian Model with Economies of Scale Ralph Gomory

SUNDAY, MARCH 22

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:15	Overview of Programming Methods and Increasing Returns Herb Scarf
10:15–10:30	*Break*
10:30–11:45	Complexity Theory Ravi Kannan
11:45 A.M.–1:00 P.M.	The Traveling Salesman Problem William Cook
1:00	Adjourn

Roster for the Workshop on Theoretical Computation in the Social Sciences, April 16–19, 1992

Prof. Michele Boldrin	Northwestern University
Prof. William A. Brock	University of Wisconsin
Dr. W. Daniel Hillis	Thinking Machines Corporation
Dr. Tad Hogg	Xerox Palo Alto Research Center
Prof. Alfred Hubler	University of Illinois
Prof. Larry Jones	Northwestern University
Prof. Kenneth Judd	Stanford University
Prof. Timothy Kehoe	University of Minnesota
Prof. Charles D. Kolstad	University of Illinois
Dr. Chris G. Langton	Los Alamos National Laboratory
Prof. Steve Lansing	University of Southern California
Prof. Blake LeBaron	University of Wisconsin
Dr. Robert Litterman	Goldman Sachs
Prof. Rodolfo Manuelli	Northwestern University
Dr. Albert Marcet	Universitat Pompeu Fabra
Prof. Ramon Marimon	Universitat Pompeu Fabra
Prof. David Marshall	Northwestern University
Prof. Rosa Matzkin	Yale University
Prof. John H. Miller	Carnegie-Mellon University
Dr. Nathan Myhrvold	Microsoft
Dr. Radha Nandkumar	National Center for Supercomputing Applications
Dr. Daniel Newlon	National Science Foundation
Prof. Norman Packard	Prediction Company
Scott Page	Northwestern University
Prof. Ariel Pakes	Yale University
Mr. James Pelkey	Santa Fe Institute
Prof. David Pines	University of Illinois
Prof. German Rojas	Northwestern University
Prof. Peter Rossi	University of Chicago
Prof. John Rust	University of Wisconsin
Prof. Martin Shubik	Yale University
Dr. Ivan Sipos	Digital Equipment Corporation
Prof. Hal R. Varian	University of Michigan
Dr. Stephen Wolfram	Wolfram Research, Inc.

Program for the Workshop on Theoretical Computation in the Social Sciences, April 16–19, 1992

THURSDAY, APRIL 16, 1992

8:30–9:00 A.M.	*Continental Breakfast*
9:00–9:15	Welcome & Introductions
9:15–9:45	Preliminary Remarks: Theoretical Computation in Economics John Miller Theoretical Computation in Astrophysics David Pines
9:45–11:00	Minimum Weighted Residual Methods for Solving Dynamic Economic Models Kenneth Judd
11:00–11:15	*Break*

11:15 A.M.–12:30 P.M.	Convergence of Approximate Model Solutions to Rational Expectations Equilibria Using the Method of Parameterized Expectations Albert Marcet and David Marshall
12:30–1:30	*Lunch*
1:30–2:45	Optimal Taxation in Models of Endogenous Growth Larry Jones, Rodolfo Manuelli, Peter Rossi
2:45–3:00	*Break*
3:00–4:15	Correlated Rationalizability Ramon Marimon and Albert Marcet
4:15–5:30	Spawn: A Distributed Computational Economy Tad Hogg

FRIDAY, APRIL 17

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:00	Artificial Adaptive Agents in Game Theory John Miller
10:00–11:00	Insights From a Computerized Double Auction Tournament John Rust
11:00–12:00 NOON	Optimization, Experimentation, and Education Hal Varian
12:00–12:45 P.M.	*Lunch*
12:45–2:00	Origins of Randomness Stephen Wolfram
2:00–3:15	Computing Markov Perfect Nash Equilibria: Numerical Implications of a Dynamic Differentiated Product Model Ariel Pakes
	FREE AFTERNOON

SATURDAY, APRIL 18

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:15	Simulation Methods for Unemployed Theorists Daniel McFadden
10:15–10:30	*Break*
10:30–11:45	Computation and Operational Properties of Nonparametric Concavity–Restricted Estimators Rosa Matzkin
11:45 A.M.–1:00 P.M.	Computational Economics: Learning Algorithms for Connecting Data to Models Norman Packard
1:00–2:00	*Lunch*
2:00– 3:15	Beyond Randomness or Emergent Noise: Interactive Systems of Traders with Dependent Characteristics William Brock
3:15– 3:30	*Break*
3:30– 4:45	Equilibrium Models with Global Asset Allocation Robert Litterman and F. Black

SUNDAY, APRIL 19

8:30–9:00 A.M.	*Continental Breakfast*
9:00– 9:30	Availability and Access to Supercomputation Radha Nandkumar
9:30–12:00 NOON	Future Directions for Theoretical Computation: Moderators: Dan Newlon and David Pines
12:00 NOON	*Adjourn*

Roster for the Workshop on Biology and Economics: Overlapping Generations, April 24–26, 1992

Prof. Stuart Altmann	University of Chicago
Dr. George Cowan	Los Alamos National Laboratory/SFI
Dr. Vincent P. Crawford	University of California, San Diego
Ms. Esther Dyson	EDventure Holdings, Inc.
Mr. Richard Epstein	Los Alamos National Laboratory
Prof. Marcus W. Feldman	Stanford University
Prof. John Geanakoplos	Yale University
Prof. Murray Gell-Mann	California Institute of Technology
Mr. Gordon Getty	Ann and Gordon Getty Foundation
Prof. Jean-Michel Granmont	CEPREMAP
Prof. Jack Hirschleifer	University of California, Los Angeles
Prof. Sara Hrdy	University of California
Ms. Debra Judge	University of California
Dr. Stuart Kauffman	Santa Fe Institute
Dr. Edward A. Knapp	Santa Fe Institute
Prof. Jane Lancaster	University of New Mexico
Dr. John McCarthy	Stanford University
Prof. Michael McGuire	University of California at Los Angeles Medical School
Mr. James Pelkey	Santa Fe Institute
Prof. Alan Rogers	University of Utah
Mr. Michael Rothschild	Bionomics Institute
Prof. Jonathan Roughgarden	Stanford University
Prof. Karl Shell	Cornell University
Prof. Martin Shubik	Yale University
Dr. L. M. Simmons, Jr.	Santa Fe Institute
Prof. Larry Slobodkin	State University of New York at Stony Brook
Prof. Robert Trivers	University of California, Santa Cruz

Program for the Workshop on Biology and Economics: Overlapping Generations, April 24–26, 1992

FRIDAY, APRIL 24

8:30–9:00 A.M.	*Continental Breakfast*
9:00–9:15	Welcome & Introductions
9:15–9:45	Preliminary Remarks Martin Shubik
9:45–11:00	Biology, Economics, and the Scandal of Cooperation Jack Hirschleifer
11:00–11:15	*Break*
11:15 A.M.–12:30 P.M.	Evolution Theory and Economics Stu Kauffman
12:30–1:30	*Lunch*
1:30–2:45	The Meaning of the Selfish Gene Robert Trivers Comments Gordon Getty
2:45–3:00	*Break*

3:00–4:15	On the Joys and Dangers of Analogies Between Ecology and Economics Larry Slobodkin
4:15–5:30	The Games Within the Game: Myopic Optimization and Evolutionary Systems Martin Shubik

SATURDAY, APRIL 25

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:15	Law and Intergenerational Justice Transfer
10:15–11:30	Can Anthropoid Primates Understand Money? Stuart Altmann
11:30–11:45	*Break*
11:45 A.M.–1:00 P.M.	Intergenerational Transfer Sarah Hrdy and Debra Judge
1:00–2:00	*Lunch*
2:00– 3:15	Learning Optimization and Competition Jonathan Roughgarden
3:15– 3:30	*Break*
3:30– 4:30	Rationality and Its Limits Michael McGuire
4:30– 5:30	Time in Biology and Economics Alan Rogers
6:30	Dinner La Tertulia Restaurant, 416 Agua Fria

SUNDAY, APRIL 26

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:15	Evolutionary Genetic Stability: Where Game and Evolutionary Theory Differ Marc Feldman
10:15–10:30	*Break*
10:30–11:45	On ESS Vincent Crawford
11:45 A.M.–1:00 P.M.	Survey of OLG John Geanakoplos Comments Karl Shell, Andreu Mas-Collel
1:00–2:00	*Lunch*
2:00– 3:15	Diversity and Stability in Biology and Economics Jean Michel Granmont
3:15– 3:30	*Break*
3:30– 5:00	Round Table

Roster for the Working Group Meeting on the Theory of Money and Financial Institutions, May 1–4, 1992

Prof. Robert Anderson	University of California, Berkeley
Prof. Pradeep Dubey	State University of New York
Mr. A. Krishna Jayawardene	Yale University
Prof. Ioannis Karatzas	Columbia University
Prof. S. Sahi	Princeton University
Prof. Lloyd Shapely	University of California, Los Angeles
Prof. Martin Shubik	Cowles Foundation
Prof. William Sudderth	University of Minnesota
Dr. Dimitri Tsomocos	Yale University

Program for the Working Group Meeting on the Theory of Money and Financial Institutions, May 1–4, 1992

Formal program not available.

Roster for the Workshop on Comparative Time Series Analysis, May 14–17, 1992

Dr. Martin Casdagli	FB Tech Joint Venture
J. Christopher Clemens	University of Texas at Austin
Mr. David Donoho	Stanford University
Dr. Doyne Farmer	The Prediction Company
Dr. Andrew Fraser	Portland State University
Dr. Neil Gershenfeld	Massachusetts Institute of Technology
Dr. Leon Glass	McGill University
Dr. Ary Goldberger	Beth Israel Hospital
Prof. Clive Granger	University of California, San Diego
Peter Grassberger	University of Wuppertal
Professor Udo Huebner	Phys.-Techn. Bundesanstalt
J.P. Huke	DRA at RSRE
Jim Hutchinson	Massachusetts Institute of Technology
Dr. Holger Kantz	University of Wuppertal
Dr. Daniel Kaplan	McGill University
Prof. Eric Kostelich	Arizona State University
Dr. Alan S. Lapedes	Los Alamos National Laboratory
Professor Blake LeBaron	University of Wisconsin
Dr. Jean Lequarre	Union Bank of Switzerland
Peter Lewis	USN Postgraduate School
Paul Linsay	Massachusetts Institute of Technology
Dr. John Moody	OGI/CSE Department
Mike Mozer	University of Colorado
Milan Palus	Beckman Institute
Dr. William Press	Harvard College Obs.
Bonnie Ray	Naval Postgraduate School
Dr. David Rigney	Beth Israel Hospital
Dr. Tim Sauer	George Mason University
Dr. Thomas Schreiber	Niels Bohr Institute
Dr. Leonard Smith	Oxford University
Prof. Harry L. Swinney	University of Texas
Dr. James Theiler	Los Alamos National Laboratory
Daniel Upper	University of California
Eric Wan	Stanford University
Dr. Andreas Weigend	Xerox Palo Alto Research Center
Xiru Zhang	Thinking Machines Corporation
Dr. Alexander Zheleznyak	Russian Academy of Science

Program for the Workshop on Comparative Time Series Analysis, May 14–17, 1992

THURSDAY, MAY 14

8:00–10:00 A.M.	*Breakfast*
9:00 A.M.–12:30 P.M.	Registration and Informal Discussion
11:00 A.M.–12:30 P.M.	*Lunch*
12:30–1:30	Introduction: Competition History, Methodology, and Results
1:30–3:00	Data Descriptions and Overviews of Time Series Problems: Physics/Astronomy
3:00–4:15	Data Descriptions and Overviews of Time Series Problems: Biology
4:15–5:30	Data Descriptions and Overviews of Time Series Problems: Mathematics/ Statistics

6:00–8:00	*Group Dinner* The Old Mexico Grill, 2434 Cerrillos Road
8:30–10:30	Time Series Analysis in Economics and Financial Markets

FRIDAY, MAY 15

8:00–9:00 A.M.	*Breakfast*
9:00–12:00 NOON	Data Analyses: Forecasting I
12:00–2:00 P.M.	*Lunch*
2:00–5:30	Data Analyses: Forecasting II:
5:30–8:00	*Dinner and Free Time*
8:00–10:00	Efficient Algorithms and Non-Traditional Architectures for Time Series Problems
10:00–?	Informal Discussions/Access to Computers

SATURDAY, MAY 16

8:00–9:00 A.M.	*Breakfast*
9:00 A.M.–1:00 P.M.	Data Analyses: System Characterization, Model Building, Including Randomness Estimation
1:00–7:00	*Bag Lunch*, Informal Discussions, Hike/Outing
7:30	Banquet and Awards at Rancho de Chimayo

SUNDAY, MAY 17

8:00–9:00 A.M.	*Breakfast*
9:00–10:00	Towards the Future: Spatio-Temporal Analysis
10:00–12:00 NOON	Conclusion: What Have We Learned?

Roster for the Workshop on What OR Models Have to Offer CAS, and Vice Versa, May 24–26, 1992

Prof. James Bean	University of Michigan
Prof. Michael Cohen	University of Michigan
Prof. Kevin Crowston	Massachusetts Institute of Technology
Prof. Stephanie Forrest	University of New Mexico
Prof. John Holland	University of Michigan
Prof. John Jackson	University of Michigan
Dr. Alan Kaufman	Massachusetts Institute of Technology
Prof. Tom Magnanti	Massachusetts Institute of Technology
Prof. Melanie Mitchell	University of Michigan/Santa Fe Institute
Dr. Steve Pollock	University of Michigan
Prof. Carl Simon	University of Michigan
Prof. Robert Smith	University of Michigan

Program for the Workshop on What OR Models Have to Offer CAS, and Vice Versa, May 24–26, 1992

SUNDAY, MAY 24

9:00–9:15 A.M.	*Coffee*
9:15–9:30	Welcome and Introductions
9:30–2:15	Each participant will spend roughly fifteen minutes presenting an overview of work in progress which lies (arguably) near an interface between the OR and CAS approaches to modeling. (The attached statements should prepare you for this part of the workshop). In the interest of keeping schedule and focus, presentations should be aimed at convincing at least one member of the audience that he or she might be able to contribute to an understanding of the problem at hand; or b) convincingly argue its triviality, impossibility or irrelevance. Questions will be constructed (!) to ones dealing with clarification only. Debates will be delayed to later in the workshop.
9:30–9:45	Holland
9:45–10:00	Pollock
10:00–10:15	Jackson
10:15–10:30	Bean
10:30–11:00	*Break*
11:00–11:15	Cohen
11:15–11:30	Kaufman
11:30–11:45	Magnanti
11:45–12:00 NOON	Forrest
12:00–1:15 P.M.	*Lunch*
1:15–1:30	Langton
1:30–1:45	Smith
1:45–2:00	Mitchell
2:00–2:15	Simon
2:15–2:30	Organization of two or three small groups in order to follow up on the morning's presentation. Our intention is to have at least one member from each "camp" in each group
2:30–4:30	Small group meetings for technical discussion involving *details* of methods, algorithms, simulations, speculations, etc.

MONDAY, MAY 25

9:00–9:15 A.M.	*Coffee*
9:15–12:00 NOON	Plenary group follow-up on previous days' discussions. Setting the agenda for the rest of the day (probably breaking up into new small groups, perhaps mutated and crossed-over according to a yet-to-be-determined fitness function.)
12:00–1:30 P.M.	*Lunch*
1:30–4:30	(T.B.A)

TUESDAY, MAY 26

9:00–12:00 NOON	Specific steps for continuation of cross-fertilization, language-sharing, possibilities for interactions in publications, professional societies, meetings.

Roster for the 1992 Complex Systems Summer School, May 31–June 26, 1992

Faculty

Prof. Robert Austin	Princeton University
Prof. Joshua Epstein	Brookings Institution
Prof. Marcus W. Feldman	Stanford University
Prof. Ray Goldstein	Princeton University
Dr. Charles Gray	The Salk Institute
Dr. Tad Hogg	Xerox Palo Alto Research Center
Prof. E. Atlee Jackson	University of Illinois
Dr. Kristian Lindgren	Chalmers University of Technology
Prof. Robert Maier	University of Arizona
Prof. Gottfried J. Mayer-Kress	University of Illinois/Santa Fe Institute
Prof. Melanie Mitchell	Santa Fe Institute
Dr. Cris Moore	Santa Fe Institute
Prof. Harold Morowitz	George Mason University
Prof. Lynn Nadel	University of Arizona
Dr. Mats Nordahl	Santa Fe Institute
Prof. Richard G. Palmer	Duke University
Dr. Steen Rasmussen	Los Alamos National Laboratory
Prof. Robert Schulman	Yale University
Prof. Daniel Stein	University of Arizona
Prof. Arthur Winfree	University of Arizona
Dr. David Wolpert	Santa Fe Institute
Dr. Charles C. Wood	Los Alamos National Laboratory
Dr. Gad Yagil	Max Planck Institute
Prof. Jonathan Yedidia	Harvard University

Students

Mr. William Alba	University of California, Berkeley
Ms. Cathleen Barczys	University of California, Berkeley
Subbiah Baskaran	Institut für Theoretische Chemie
Dr. Mark Beaumont	Queen Mary & Westfield College
Mr. Mark Bieda	Stanford University
Dr. Laura Bloom	University of California, San Diego
Mr. Eric Bonabeau	Ecole Normale Supérieure
Mr. T. David Burns	George Mason University
Mr. Lars-Erik Cederman	University of Michigan
Mr. Ernest P. Chan	Cornell University
Mr. Victor Hok-kiu Chan	University of Southern California
Dr. Milos Dolnik	Brandeis University
Dr. Igor I. Fedchenia	Umea University
Mr. Barry Feldman	State University of New York at Stony Brook
Dr. Petra Foerster	Stanford University
Dr. Christopher Georges	Hamilton College
Mr. David S. Graff	University of Michigan
Dr. Alan Horowitz	University of Pittsburgh
Dr. Alex S. Kaganovich	GEOS, Moscow
Dr. Alan Kaufman	Massachusetts Institute of Technology
Ms. Leslie M. Kay	University of California, Berkeley
Mr. Brian L. Keeley	University of California, San Diego

Ms. Helen A. Klein	University of Michigan
Mr. John M. Kovac	Princeton University
Mr. Chi-Hang Lam	University of Michigan
Mr. Gerald J. Lapeyre	University of Arizona
Dr. Bennett S. Levitan	University of Pennsylvania
Jing Li	Brandeis University
Mr. Tim Linger	University of Vermont
Mr. Jonathon Mattingly	Yale University
Dr. Katarzyna Michalska	Warsaw Agricultural University
Kai Nagel	University of Cologne
Dr. David A. Noever	NASA Space Science Laboratory
Kihong Park	Boston University
Lieke Peper	Faculty of Human Movement Sciences
Mr. Garry D. Peterson	University of Florida
Thea Philliou	University of New Mexico
Dr. Miriam Reiner	Technion
Ms. Anastasia Ruzmaikina	University of Arizona
Ms. Orit Saigh	Brandeis University
Mr. Theodore Sande	Massachusetts Institute of Technology
Dr. Stefan Schaal	Massachusetts Institute of Technology
Dr. Zdenek Schindler	Czech. Academy of Sciences
Ms. L. Ruth Silber	Princeton University
Mr. Derek J. Smith	University of New Mexico
Ms. Una R. Smith	Duke University
Mr. Dagmar Sternad	Free University of Amsterdam
Mr. Josh Tenenbaum	Yale University
Dr. Tony Varghese	AHPCRC
Mr. Randal J. Verbrugge	Stanford University
Ms. Zuzana Vespalcova	University of Leeds
Mr. Hans von Gizycki	City College of New York
Minchun Wu	Princeton University
Dr. Daniel K. P. Yip	University of Southern California
Henggui Zhang	University of Leeds

Program for the 1992 Complex Systems Summer School, May 31–June 26, 1992

WEEK ONE, MAY 31-JUNE 6

Sunday, May 31

1:00–8:30 P.M.	Registration–Second Floor, Peterson Student Center
6:00–8:30	Welcoming Reception– Senior Commons Room, Second Floor, Peterson Student Center

Monday, June 1
(All meetings take place in the Great Hall, Peterson Student Center, unless otherwise noted.)

8:30 A.M.	Welcoming Remarks Ed Knapp, President, Santa Fe Institute
8:45	Introduction to the 1992 Complex Systems Summer School Daniel Stein, Program Co-Director
9:00	The SFI Approach to Complexity L.M. Simmons, Jr., V.P. for Academic Affairs, Santa Fe Institute
10:30	*Break*

10:45	Rhythmic Oscillations of the Brain Charles Gray
12:15 P.M.	*Lunch*–Dining Room, First Floor, Peterson Student Center
1:30	An Introduction to Santa Fe and Northern New Mexico Andi Sutherland, Program Coordinator, Santa Fe Institute
3:30	Genetic Algorithms Melanie Mitchell
Tuesday, June 2	
9:00 A.M.	Genetic Algorithms Melanie Mitchell
10:30	*Break*
10:45	Rhythmic Oscillations of the Brain Charles Gray
12:15 P.M.	*Lunch*
1:30	Introduction to Neural Network Computation Richard Palmer
4:00	Tour of Summer School Computer Lab Brent McClure, Systems Manager
7:30	Computational Theory of Early Visual Processing Kihong Park, Boston University **
Wednesday, June 3	
9:00 A.M.	Genetic Algorithms Melanie Mitchell
10:30	*Break*
10:45	Rhythmic Oscillations of the Brain Charles Gray
12:15 P.M.	*Lunch*
1:30	Chaos Concepts Atlee Jackson, University of Illinois & SFI
3:00	University of New Mexico Graduate Credit Registration (Outside Great Hall)
4:30	Spatio-Temporal Dynamics of Human EEG during Somatosensory Perception Cathleen Barczys, UC, Berkeley **
7:30	Using GA's to Evolve Turing Machines to Solve the Busy Beaver Problem Terry Jones, Indiana University **
Thursday, June 4	
9:00 A.M.	Genetic Algorithms Melanie Mitchell
10:30	*Break*
10:45	Rhythmic Oscillations of the Brain Charles Gray
12:15 P.M.	*Lunch*
1:30	Spin Glasses: An Introduction to Randomness in Physical Systems Daniel Stein
4:30	Dynamics of Rat EEG During Olfactory Perception: The Search for Reafference Leslie Kay, UC, Berkeley **

Friday, June 5	
9:00 A.M.	Genetic Algorithms Melanie Mitchell
10:30	*Break*
10:45	Rhythmic Oscillations of the Brain Charles Gray
12:15 P.M.	*Lunch*
1:30	An Introduction to Mapping the Brain Charles Wood, Los Alamos National Laboratory

WEEK TWO, JUNE 7-13

Sunday, June 7	
6:30–8:30 P.M.	Informal Social Gathering: Senior Commons Room
Monday, June 8	
9:00 A.M.	The Ecology of Computation Tad Hogg, Xerox PARC
12:15 P.M.	*Lunch*
1:30	Global Methods for Cellular Automata Steen Rasmussen, Theoretical Division, LANL
3:00	Evolution and Optimization: They're Not the Same Marcus Feldman, Stanford University
6:30	Neurobiology Workshop Victor Chan **
7:30	Philosophical Issues in Complexity Brian Keeley, UC, San Diego **
Tuesday, June 9	
9:00 A.M.	The Ecology of Computation Tad Hogg, Xerox PARC
10:30	*Break*
10:45	Evolutionary Phenomena in Simple Dynamics Kristian Lindgren, Santa Fe Institute
12:15 P.M.	*Lunch*
1:30	Slow Relaxation in Complex Systems Richard Palmer
4:30	Signal-Processing Based Modeling of the Retina Bennett Levitan **
7:30	Noise-Induced Chaos in the Lorenz Model: Can We Distinguish Noise and Chaos? Igor Fedchenia, Umea University **
10:30	Bill Moyers' Telecast: "A Sustainable World" Senior Commons Room, Peterson Student Center
Wednesday, June 10	
9:00 A.M.	The Ecology of Computation Tad Hogg, Xerox PARC
10:30	*Break*

10:45	Evolution of Artificial Food Webs Kristian Lindgren, Santa Fe Institute
12:15 P.M.	*Lunch*
1:30	Introductory Presentations by SFI Researchers How to Deal With Multiple Generalizers–David Wolpert T.B.A.–Mats Nordahl T.B.A.–Chris Moore
7:30	Computational Approaches to Preattentive Vision Josh Tenenbaum **
Thursday, June 11	
9:00 A.M.	The Ecology of Computation Tad Hogg, Xerox PARC
10:30	*Break*
10:45	Biochemical Networks and Antichaotic Behavior Harold Morowitz
12:15 P.M.	*Lunch*
4:00	A-Life versus R-Life Discussion
7:30	Chaos and Oscillator-Coupling in the Kidney Microcirculation Daniel Yip **
Friday, June 12	
9:00 A.M.	The Ecology of Computation Tad Hogg, Xerox PARC
10:30	*Break*
10:45	Experimental Artificial Biochemistry Harold Morowitz
12:15 P.M.	*Lunch*
1:30	Self-Programming Steen Rasmussen, Theoretical Division, LANL

WEEK THREE, JUNE 14-20

Sunday, June 14	
6:30–8:30 P.M.	Informal Social Gathering Senior Commons Room
Monday, June 15	
9:00 A.M.	The Geometry of Excitability Art Winfree
10:30	*Break*
10:45	Quenched Disorder Jonathan Yedidia
12:15 P.M.	*Lunch*
1:30	Complex Analysis: A Molecular Biologist's Approach Gad Yagil, Cellular Biology, Weizmann Institute, Israel
3:00	Afternoon free for attendance of Alife III conference
Tuesday, June 16	
9:00 A.M.	The Geometry of Excitability Art Winfree

10:30	*Break*
10:45	Quenched Disorder Jonathan Yedidia
12:15 P.M.	*Lunch*
1:30	Afternoon free for attendance of Alife III conference
Wednesday, June 17	
9:00 A.M.	The Geometry of Excitability Art Winfree
10:30	*Break*
10:45	Quenched Disorder Jonathan Yedidia
12:15 P.M.	*Lunch*
1:30	Afternoon free for attendance of Alife III conference
Thursday, June 18	
9:00 A.M.	The Geometry of Excitability Art Winfree
10:30	*Break*
10:45	Quenched Disorder Jonathan Yedidia
12:15 P.M.	*Lunch*
1:30	Afternoon free for attendance of Alife III conference
Friday, June 19	
9:00 A.M.	The Geometry of Excitability Art Winfree
10:30	*Break*
10:45	Quenched Disorder Jonathan Yedidia
12:15 P.M.	*Lunch*
1:30	Afternoon free for attendance of Alife III conference

WEEK FOUR, JUNE 21-26

Sunday, June 21	
6:30–8:30 P.M.	Informal Social Gathering Senior Commons Room
Monday, June 22	
9:00 A.M.	Protein Biophysics Robert Austin
10:30	*Break*
10:45	The Mathematical Biology of Arms Races and Wars Joshua Epstein, The Brookings Institution
12:15 P.M.	*Lunch*
1:30	Global Information Systems and Nonlinear Methodologies in Crisis Management Gottfried Mayer-Kress, CCSR, University of Illinois

4:30	Comparing Different Approaches for Modelling the Hypercycle Zuzana Vespalcová** PSC-1, First floor, Peterson Student Center
6:30	From Random Systems to Surface Growth in Random Media Alex Kaganovich ** PSC-1, First floor, Peterson Student Center
Tuesday, June 23	
9:00 A.M.	Protein Biophysics Robert Austin
10:30	*Break*
10:45	Revolutions and Epidemics Joshua Epstein, The Brookings Institution
12:15 P.M.	*Lunch*
1:30	Large Fluctuations in Stochastically Modeled Nonlinear Systems Robert Maier
5:30	Meet at fish pond to caravan to Rancho de Chimayó
6:30	*Dinner* at Rancho de Chimayó
Wednesday, June 24	
9:00 A.M.	Protein Biophysics Robert Austin
10:30	*Break*
10:45	Nonlinear Dynamics of Drug Addiction Joshua Epstein, The Brookings Institution
12:15 P.M.	*Lunch*
1:30	NMR Studies of Brain Function Robert Schulman
4:30	Political and Economic Implications of Chaos David Burns **
8:00	SFI Lecture (open to the public) Complex Systems, Nonlinear Dynamics, and Global Welfare Joshua Epstein, The Brookings Institution
Thursday, June 25	
9:00 A.M.	Nonlinear Dynamics of Pattern Formation in Physics and Biology Ray Goldstein
10:30	*Break*
10:45	Some Counter-Intuitive Results on Ecosystem Stability Joshua Epstein, The Brookings Institution
12:15 P.M.	*Lunch*
4:30	Freeway Traffic, Cellular Automata, and some Self-Organizing Criticality Kai Nagel **
7:30	Characterization of the Spatio-Temporal Complexity for a Coupled-Map–Lattice Neural Computing System Henggui Zhang **
Friday, June 26	
9:00 A.M.	Nonlinear Dynamics of Pattern Formation in Physics and Biology Ray Goldstein
10:30	*Break*

10:45	Using Neural Networks to Predict Currency Exchange Rates Joshua Epstein, The Brookings Institution
12:30 P.M.	*Final Lunch*–Meem Library Placita

Roster for the Workshop on Artificial Life III, 1992

Dr. Lloyd Allred	NERDS
Prof. Peter Angeline	Ohio State University
Mr. Spiro Antonopoulos	boing boing
Prof. Daniel Ashlock	Iowa State University
Mr. Andrew Assad	CCSR, U. Illinois
Mr. Paul E. Baclace	Autodesk, Inc.
Mr. William Baggett	Memphis State University
Mr. Alan Bahm	Reed College
Mr. Andrew Banas	Tufts University
Dr. Paul Barton-Davis	University of Washington
Prof. Mark Bedau	Reed College
Prof. Randall Beer	Case Western Reserve University
Mr. Michel Bera	MATRA Corporate
Mr. Howard Bergh	University of California, Santa Barbara
Mr. Haim Bodek	University of Rochester
Prof. Paul Bourgine	CEMAGREF
Mr. Michael Bremer	Maxis
Mr. Bill Bumgarner	Stone Design
Prof. V. Calenbuhr	Université Libre de Bruxelles
Dr. John Casti	Santa Fe Institute
Prof. Kwok Hung Chan	Memphis State University
Mr. Frank Chang	Sandia National Labs
Dr. Pat Churchland	University of California, San Diego
Dr. Paul Churchland	University of California, San Diego
Mr. Eric Cooper	Apple Computer Advanced Technology
Mr. Theodore Cotter	Los Alamos, New Mexico
Mr. Bill Cozad	Corrales, New Mexico
Mr. Peter Dapkus	University of California, San Diego
Prof. Pranab Das	University of Texas, Austin
Dr. Rajarshi Das	Colorado State University
Dr. Sreerupa Das	University of Colorado, Boulder
Mr. Robert Davidge	University of Sussex
Prof. Craig Davis	San Diego State University
Mr. Mark Davis	New Mexico State University
Dr. Randy Davis	Massachusetts Institute of Technology
Dr. Hugo de Garis	Electrotechnical Lab
Mr. Guillaume Deffuant	CEMAGREF
Mr. Claude Delaye	Laforia Université Paris VI
Mr. John Deming	Palo Alto, CA
Ms. Lisa Desjarlais	University of New Mexico
Mr. Dwight Deugo	Carleton University
Prof. Scott Dodson	Memphis Speech and Hearing Center
Mr. Alexis Drogoul	Laforia Université Paris VI
Mr. Jake Eagle	NLP Santa Fe
Prof. Frederick Eirich	Polytechnic University
Mr. Hilaire Epesse	CEMAGREF
Mr. Gregor Erbach	Universität Saarbrücken
Prof. Nils Ferrand	ENGREF
Mr. Alan Filipski	Arizona State University
Mr. Charles Fitzgerald	Microsoft Corporation
Mr. Bruce Gaber	Na[illegible] Research Laboratory

Mr. John Gallagher	Case Western Reserve University
Mr. Anthony Garcia	Microsoft Corporation
Mr. Simon Garton	University of California, San Diego
Mr. R. Garwood	Birmingham, MI
Mr. Nicholas Gessler	University of California, Los Angeles
Dr. Wanda Gleason	Massachusetts Institute of Technology
Prof. Peter Godfrey-Smith	Stanford University
Mr. Takashi Gomi	Applied AI Systems
Prof.Susantha Goonatilake	New School for Social Research
Mr. Wayne Grant	Apple Computer Advanced Technology
Prof. Emanuel Gruengard	Bar-Ilan University
Mr. Martin Haeberli	Apple Computer Advanced Technology
Mr. R.V. Hamlin	Sun Design
Mr. Simon Handley	Stanford University
Prof. Stevan Harnad	Princeton University
Dr. Robin Harper	Maxis
Mr. William Hart	*The Dallas Morning News*
Dr. Ralph Hartley	Naval Research Lab
Inman Harvey	Sussex University
Mr. Katsura Hattori	The Asahi Shim-bun
Mr. Kevin Haynes	University of California, San Diego
Prof. Lewis Held	Texas Technical University
Dr. Richard Hess	DuPont Fibers
Mr. Dave Hiebler	Thinking Machines Corporation
Mr. Ron Hightower	University of New Mexico
Mr. John Hiles	Delta Logic
Dr. Uwe Hobohm	EMBL
Mr. Shinichi Honda	The Asahi Shim-bun
Mr. Daniel Hopkins	Beam Robotics
Mr. Jeffery Horn	University of Illinois
Mr. Andrew Horner	University of Illinois
Mr. Hirokaza Hotani	Teikyo University
Dr. Laura Hubler	University of Wisconsin, Madison
Prof. Philip Husbands	University of Sussex
Dr. Takashi Ikegami	Kobe University
Dr. Dean Inada	Questrel, Inc.
Mr. Jeff Inman	Santa Fe, NM
Prof. Keisuke Ito	Kobe University
Dr. Eric Iverson	New Mexico State University
Dr. Greg James	University of Calgary
Mr. Steven Janke	Colorado College
Mr. Tim Jenison	New Tek, Inc.
Mr. George Johnson	*The New York Times*
Mr. Michael Johnson	Massachusetts Institute of Technology Media Lab
Mr. Ted Kaehler	Apple Computer, Inc.
Dr. George Kampis	University of Tübingen
Kunihiko Kaneko	University of Tokyo
Mr. Ken Karakotsios	Maxis
Dr. Alan Kaufman	Massachusetts Institute of Technology
Dr. Sanza Kazadi	California Institute of Technology
Mr. Brian L. Keeley	University of California, San Diego
Mr. Timothy Keitt	University of New Mexico
Mr. Gary E. Kelly	Hill Air Force Base
Mr. Kevin Kelly	Point Foundation

Mr. Paul Kennedy	University of Technology, Sydney
Mr. Jeff Kephart	IBM T.J. Watson Research Center
Mr. David Kilman	Memphis State University
Dr. Jan Tai Tsung Kim	Max Planck Institut
Mr. Kim Kinnear	Sun Microsystems
Prof. Bjorn Kirkerud	University of Oslo
Kim A. Kirkpatrick	New Mexico Highlands University
Ms. Shirley Kitts	Brighton Polytechnic
Mr. Gene Korienek	Artifact, Inc.
Mr. Henry Kressel	New York, NY
Mr. John LaBry	Silicon Graphics
Mr. Brian Ladner	University of California, San Diego
Mr. Mark Langston	Memphis State University
Mr. Benny Lautrup	Niels Bohr Institute
Mr. Marc Lavenant	University of Chicago
Mr. Steven Levy	Otis, MA
Mr. Michael Littman	Bellcore
Mr. Minghsun Liu	Massachusetts Institute of Technology
Mr. Richard Long	IST/UCF
Mr. Treg Loyden	Tempe, AZ
Prof. Pier Luisi	Institut für Polymere
Ms. Grace Lyo	Sandia High School
Mr. John Lyo	Sandia National Laboratories
Dr. Pattie Maes	Massachusetts Institute of Technology
Prof. Carlo Maley	Oxford University
Arun Malik	Harvard Business School
Ms. Marlene Mallicot	Xanadu
Prof. Francis Marchese	Pace University
Mr. James Marshall	Indiana University
Mr. Fred Martin	Massachusetts Institute of Technology
Prof. Jerzy Maselko	University of Alaska
Ms. Maja Mataric	Massachusetts Institute of Technology AI Lab
Kazuhiro Matsuo	Fujitsu Laboratories Ltd.
Mr. Justin McCormick	Maxis
Mr. David McFadzean	University of Calgary
Mr. Gary McGraw	Indiana University
Mr. Michael McKenna	Massachusetts Institute of Technology Media Lab
Mr. Phil Mercurio	San Diego Supercomputer Center
Mr. Dana Meyer	Working Knowledge
Mr. Ilko Michler	Technical University of Munich
Mr. Arthur Miller	Northeastern University
Dr. Geoffrey F. Miller	Stanford University
Mr. Nelson Minar	Reed College
Mr. Eric Minch	Stanford University Medical Center
Mr. Eric Mjolsness	Yale University
Mr. Etienne Monneret	CEMAGREF
Mr. Bob Moore	New York, NY
Dr. Federico Moran	Universidad Complutense
Mr. Peter Moyneux	Bullfrog
Prof. Koichi Murakami	Carnegie-Mellon University
Mr. Kourosh Nafisi	University of California, Los Angeles
Prof. Suma Noji	Nippon Electronics College
Prof. Stefano Nolfi	Institute of Psychology, C.N.R.
Mr. James Nugen	Columbus, OH

Mr. Craig O' Brien	University of Rochester
Mr. Michael Oliphant	University of California, San Diego
Prof. Franz Oppacher	Carleton University
Ms. Hope Ortiz	New Mexico State University
Mr. Michael Palmiter	Alhambra High School
Mr. Nutan Panda	DuPont Nemours
Dr. Domenico Parisi	University of California, San Diego
Mr. Sean Patrick	Valley High School
Mr. Howard Pearlmutter	Softweaver
Mr. Tim Perkis	Albany, CA
Dr. Markus Peschl	University of Vienna
Mr. Marc Pestana	University of California, Los Angeles
Dr. Ugo Piazzalunga	Institute of Psychology, C.N.R.
Ms. Leslie Picardo	Case Western Reserve University
Mr. Vladimir Pokhilko	Bulletproof Software
Mr. Alexander Pol	University of Miami
Mr. Otis Port	Business Week
Dr. Robert Price	JAYCOR
Prof. Dr. P. Prusinkiewicz	University of Calgary
Mr. Ivan Pulleyn	University of Rochester
Prof. Jeff Putnam	NM Institute of Mining & Technology
Prof. Felix Putters	University of Leiden
Mr. Josh Quitter	*Newsday*
Prof. Julius Rebek	Massachusetts Institute of Technology
Dr. John Reinitz	Yale University Medical School
Mr. Craig Reynolds	Symbolics Graphics Division
Mr. Edward Rietman	AT&T Bell Laboratories
Mr. Gary Roberts	University of Edinburgh
Mr. Eric Roffman	Personal Media International
Mr. Steve Rooke	Tucson, AZ
Mr. Donald Rose	Creative Consulting
Prof. Michael Roth	Johns Hopkins University
Mr. Rudy Rucker	Autodesk, Inc.
Mr. Wheeler Ruml	Harvard University
Dr. Randy Sargent	Massachusetts Institute of Technology
Mr. Robert Schmieder	Sandia National Laboratories
Mr. Franz Schönbauer	Technical University of Vienna
Mr. Dewey Schorre	Ojai, CA
Nicol Schraudolph	University of California, San Diego
Prof. Johnathan Schull	Haverford College
Mr. Dan Shawver	University of New Mexico
Dr. Katsunori Shimohara	ATR A&V Perception Res.
Mr. Shigeru Shinbori	Uchidate Co., Ltd.
Mr. Chris Short	New Mexico State University
Mr. Jim Simmons	Walt Disney Computer Software
Mr. Karl Sims	Thinking Machines Corporation
Mr. Andrew Singer	Interval Research Corporation
Mr. Laszlo Sipos	The Royal Institute of Technology
Mr. Paul Skokowski	Lawrence Livermore National Laboratory
Dr. David Small	Massachusetts Institute of Technology
Mr. Mike Smit	University of Waterloo
Mr. Joshua Smith	Cambridge University
Mr. Stephen Smith	Thinking Machines Corporation
Prof. J.G. Smits	Boston University

Dr. Bruno Sobral	California Institute of Biological Research
Prof. Robert Solovay	University of California, Berkeley
Mr. Henry Stanton	MIT Press
Dr. Marcin Stegawski	Portland State University
Mr. Gregory Stevens	University of Rochester
Mr. Jason Stewart	BMC
Mr. Andrew Stone	Stone Design Corporation
Dr. Anastasia Svirezheva	Cranfield Institute of Technology
Mr. Adam Swift	Stone Design
Dr. Gilbert Syswerda	BBN Labs
Mr. Jeremy Taylor	Nova—WGBH
Prof. Leigh Tesfatsion	Iowa State University
Prof. George Theodoridis	University of Virginia
Mr. Levi Thomas	Freelance Ink
Mr. Mark Tilden	University of Waterloo
Mr. David Tilley	Eastman Kodak Company
Mr. Ted Toal	Software Science
Dr. Peter Todd	Stanford University
Dr. Peter M. Todd	Stanford University
Prof. Yukihiko Toquenaga	University of Tsukuba
Mr. Adam Trissel	San Francisco, CA
Mr. Toshiharu Tsujinaka	The Asahi Shimbur
Mr. Patrick Tufts	Brandeis University
Prof. Sherry Turkle	Massachusetts Institute of Technology
Prof. Kanji Ueda	Kobe University
Prof. Noboru Ueda	Kumamoto University
Dr. Tatsuo Unemi	Laboratory for Fuzzy Engineering Research
Dr. Jari Vaario	University of Tokyo
Dr. Kathryn Vaughn	Massachusetts Institute of Technology Media Lab
Mr. Jeffrey Ventrella	Syracuse University
Prof. Günter von Kiedrowski	Georg-August-Universität
Ms. Marÿke Vonk	Leiden University
Mr. Scott Vorthmann	Carnegie-Mellon University
Mr. Craig Walker	Sandia National Labs
Mr. David Wells	University of California, Los Angeles
Mr. Richard Welykochy	University of Technology, Sydney
Mr. Tilmann Wendel	Ohio State University
Dr. Gregory Werner	University of California, Los Angeles
Mr. John Wharton	Applications Research
Mr. Andy Wilcox	University of Florida
Mr. Uri Wilensky	Arlington, MA
Dr. Lynwood Wilson	Boulder, CO
Prof. William Wimsatt	University of Chicago
Mr. Ed Wintner	Massachusetts Institute of Technology
Mr. Steve Witham	Software Maintenance & Development Systems
Mr. Dan Wood	Thinkalong Software, Inc.
Mr. Thomas Wrensch	Boulder, CO
Mr. Richard Wyckoff	Indiana University
Mr. Allan Wylde	Springer Verlag
Mr. Larry Yaeger	Apple Computer
Dr. Gad Yagil	Max Planck Institute
Dr. Philip Zimmerman	Boulder Software Eng.
Mr. Guangzhou Zou	Texas A&M University

Ms. Andrea Zucker	Georgia State University
Prof. Martin Zwick	Portland State University

Program for the Workshop on Artificial Life III, 1992

SUNDAY, JUNE 14

5:00–8.:30 P.M.	Registration Reception (Hotel Santa Fe)

MONDAY, JUNE 15: WETWARE SYNTHESIS (SWEENEY CENTER)

9:00 A.M.	Welcome and Introduction C. Langton
9:15	Evolving Molecules for Fun and Profit G. Joyce
10:00	Applied Molecular Evolution S. Kauffman
10:45	*Break*
11:45	Self-Reproducing Molecular Machines G. von Kiedrowski
12:00 NOON	Recognition and Replication J. Rebek
12:45 P.M.	*Lunch*
12:45	Artificial Biochemistry: Life Before Enzymes H. Morowitz
3:00	Towards the Synthesis of Self-Replicating Micelles and Liposomes P. Luisi
3:45	*Break*
4:15	Artificial Liposomers B. Gaber
5:00	Cell-Like Liposomes Made by Assembly of Encapsulated Cytoskeletal Proteins H. Hotani
6:15–7:30	*Conference Reception*
7:00	Poster Session
8:00	Seminars: *Logo, Tierra, Lego-Logo

TUESDAY, JUNE 16: SOFTWARE SYNTHESIS

Morning Session:

8:00 A.M.	A Viral Computing Environment F. Cohen
8:45	*Break*
9:00	The Role of Information Flow in Morphogenesis P. Prusinkiewicz
9:45	How Simple Can a Complex System Be? S. Wolfram
10:30	*Break*
11:00	Artificial Life to Study Ecology and Population Biology C. Taylor

11:45	The Gods of the Countryside: Emergent Properties of Balinese Water Temple Networks S. Lansing
12:30 P.M.	*Lunch*
Afternoon Session:	
	Session 1 (Main floor): Social Structure, Swarm Intelligence, and Collective Behavior
2:00	Trails, Patterns, and Decision in Social Insects V. Calenburg
2:45	Towards a Dynamical Ethlogical Theory F. Putters and M. Vonk
3:10	An Adaptive Algorithm Based on the Ant Colony Metaphor M. Dorigo and P. Caironi
3:35	*Break*
4:00	A Connectionist Theory of Swarm Intelligence and Morphogenesis M. Millonas
4:45	Prisoner's Dilemma with Choice and Refusal A. Stanley, D. Ashlock, and L. Tesfatsion
	Session II (Meeting room 1): Structure Development and Behavior
2:00 P.M.	A Connectionist Model of Phylogeny J. Reinitz
2:45	Growing Neural Networks S. Nolfi
3:10	Spatial Distribution of an Evolving Population of Neural Networks U. Piazzalunga
3:35	*Break*
4:00	Artificial Embryology: The Genetic Programming of Shapes H. de Garis
4:45	The Advent of Multicellularity and the Neighborhood Coherence Principle M. and J. Phipps
5:10	Spatial Self-Structuring and Selection in Catalytic Nets of Replicators M. Boerlijst
5:30	*Dinner*
Evening Sessions:	
7:00	Emergence and Philosophy of Alife (Meeting Room 2)
7:30	Videos and Demonstrations (Main Floor):
	Virtual Laboratory in Biology P. Prusinkiewicz
	Simulation of Multicellular Development K. Fleischer
	Lizzy: A GenNet-Based Artificial Nervous System, and Evolution of Artificial Embryos on a Connection Machine H. de Garis
	The Devore Universal Computer Constructor R. Hightower

A Food Seeker Based on an Instance-Based Reinforcement Learning Method
T. Unemi

Special Effects Excerpts from "Batman Returns"
A. Kopra via C. Reynolds

Simulated Evolution for the Classroom
M. Palmiter

Bugland: The Evolution of Complex Phenotypes
R. Rucker

Model Building and Biota
B. Wimsatt

Virtual Creature System
K. Marakami

A Model of Evolution of Plant Growth Patterns Based on L-Systems and a Genetic Algorithm
J. Kim and K. Stuber

7:30 Genetic Programming Tutorial (Meeting Room 1)

WEDNESDAY, JUNE 17: SOFTWARE SYNTHESIS

Morning Session: Evolution

8:00 A.M. Evolution in Digital Organisms
T. Ray

8:45 Evolution in the GPP
J. Koza

9:30 *Break*

10:00 A Case for Distributed Lamarckian Evolution
D. Ackley and M. Littman

10:45 Artificial Food Webs
K. Lindgren and M. Nordahl

11:00 Break

11:45 "The Arrival of the Fittest"
L. Buss and W. Fontana

12:45 P.M. *Lunch*

Afternoon Sessions:

Session I (Main Floor): Simulators for Artificial Life

2:15 Polyworld: Life in a New Context
L. Yeager

3:00 Artificial Life Worlds as Discovery Environments for Learning
W. Grant

3:25 Bio-Land: An Artificial World for Evolving Communication Among Cooperating/Competing Populations of Neural Networks
G. Werner and M. Dyer

3:50 *Break*

4:15 Simulation of Autonomous Legged Locomotion
D. Zeltzer and McKenna

5:00 BioSim: An Artificial Life Playground
K. Karakotsios

5:25	Ecological Dynamics of Game World K. Matsuo
	Session II (Meeting Room 1): Evolution (continued)
2:15 P.M.	Evolution Without Natural Selection P. Todd and G. Miller
3:00	The Evolution of Sexual Selection and Female Choice R. Collins
3:25	The Evolution of Modular Computer Programs P. Angeline
3:50	*Break*
4:15	Evolutionary Activity as an Order Parameter for Evolution M. Bedau, N. Minar, and N. Packard
5:00	Fitness and Adaption of Digital Organisms W. Tackett
5:25	Interactions Among Organisms J. Horn
5:50	*Dinner*
7:30	*Evening Sessions* (Main floor): Videos and Demonstrations

THURSDAY, JUNE 18: SOFTWARE SYNTHESIS

Morning Session:	Robotics
8:00 A.M.	Basic Concepts in Robo-Biology M. Tilden
8:45	*Break*
9:00	Artificial Life Outside the Computer R. Brooks
9:45	Piezoelectric on Silicon Biomorph Microrobotics J. Smits
10:30	*Break*
11:00	Morphological and Behavioral Adaptation of Robots Using Genetic Algorithms C. Delaye and J. Ferber
11:45	Evolutionary Robotics and SAGA: The Case for Hill Crawling and Tournament Selection I. Harvey
12:30 P.M.	*Lunch*
Afternoon Sessions:	
	Session I (Main floor): Dynamics, Topology, and Connectivity
2:00 P.M.	Homeochatic Stability of Symbiotic Network with Population Dynamics and Evolving Mutation Rates K. Kaneko and T. Ikegami
2:45	The Ghost in the Machine: Basin of Attraction Fields of Disordered Cellular Automata A. Wuensche
3:30	*Break*
4:00	How Topology Affects Population Dynamics J. Kephardt

4:25	The Interplay Between the Dynamics and the Metadynamics of the Immune Network H. Bersini
4:50	From Connectionist Networks to Mathematical Animals G. Deffuant
	Session II (Meeting room 1): Robotics (continued)
2:00 P.M.	Evolving Continuous-Time Recurrent Neural Networks for Adaptive Agent Control R. Beer and J. Gallagher
2:45	From Interaction to Intelligent Behavior M. Mataric
3:10	Learning Engineering Through Robotic Design F. Martin
3:35	*Break*
4:00	C. Elegans: A Proposal to Simulate the Intelligence of a Simple Animal R. Hartley
4:25	The Coevolution of Artificial Life, Genes and Culture S. Goonatilake
5:30–7:00	Alife Cafe: Food, beer, and wine available at Sweeney Center
	Evening Session: Philosophical Discussion and Debate
7:00	Stevan Harnard
7:45	Paul Churchland
8:30	Panel discussion and audience questions

FRIDAY, JUNE 19: ARTIFICIAL "4H-SHOW"

8:00 A.M.–3:00 P.M.	Artificial "4H-Show"
3:00 P.M.	Awards Ceremony
4:00 P.M.	Conference closes

Thanks to our sponsors: The Santa Fe Institute, Los Alamos National Laboratory, and the Advanced Technology Group at Apple Computer.

Roster for the the Integrative Workshop: Common Principles of Complex Systems, July 8–15, 1992

Note: An * indicates auditors.

Prof. Philip W. Anderson	Princeton University
Prof. Kenneth J. Arrow	Stanford University
Prof. W. Brian Arthur	Stanford University
Dr. Per Bak	Brookhaven National Laboratory
Dr. James H. Brown	University of New Mexico
Prof. Leo Buss	Yale University
Ms. Elizabeth Corcoran*	Scientific American
Dr. George Cowan	Los Alamos National Laboratory
Prof. James Crutchfield	University of California at Berkeley
Ms. Esther Dyson*	EDventure Holdings, Inc.
Prof. Joshua Epstein	Brookings Institute
Prof. Marcus W. Feldman	Stanford University
Dr. Walter Fontana	Santa Fe Institute
Prof. Hans Frauenfelder	Los Alamos National Laboratory
Prof. Murray Gell-Mann	California Institute of Technology
Prof. Brian C. Goodwin	The Open University
Dr. George Gumerman*	Southern Illinois University at Carbondale
Prof. John Holland	University of Michigan
Professor Alfred Hubler	University of Illinois
Dr. Erica Jen	Los Alamos National Laboratory
Mr. George Johnson*	*New York Times*
Dr. Stuart Kauffman	Santa Fe Institute
Dr. Edward A. Knapp	Santa Fe Institute
Dr. Chris G. Langton	Los Alamos National Laboratory
Dr. Alan S. Lapedes	Los Alamos National Laboratory
Dr. Seth Lloyd	Los Alamos National Laboratory
Mr. Ben Martin	Stanford University
Mr. Robert Maxfield*	Saratoga, CA
Dr. John Maynard Smith	University of Sussex at Brighton
Dr. Nathan Myhrvold*	Microsoft Corp.
Mr. James Pelkey*	Santa Fe Institute
Dr. Alan Perelson	Los Alamos National Laboratory
Prof. David Pines	University of Illinois
Dr. Ernst Reinhard Piper*	Piper Verlag
Dr. Steen Rasmussen	Los Alamos National Laboratory
Dr. Peter Schuster	Institut fur Molekulare Biotechnologie
Dr. L. M. Simmons, Jr.	Santa Fe Institute
Dr. Charles Stevens	The Salk Institute
Dr. Mitch Waldrop*	Washington, D.C.

Program for the the Integrative Workshop: Common Principles of Complex Systems, July 8–15, 1992

WEDNESDAY, JULY 8

9:00 A.M.	Convene meeting: Chairperson
9:05	Welcome: SFI President
9:15	Introductory Statement; Goals and Objective of the Meeting: Chairperson
9:30–10:30	Introduction to Complexity: Phil Anderson
10:30–10:45	*Break*

PART I:	FUNDAMENTAL CONCEPTS
	Chairperson: L.M. Simmons, Jr.
10:45–11:45	Complexity and Complex Adaptive Systems: Fundamental Concepts and Questions: Murray Gell-Mann
11:45 A.M. -12:30 P.M.	Discussion, General and Groups
12:30	*Lunch*
Afternoon	Chairperson: David Pines
1:15-2:15	Chris Langton
2:15-2:30	Discussion
2:30-3:30	Marc Feldman
3:30-3:45	Discussion
3:45-4:00	*Break*
4:00-5:00	Emerging Mathematical and Computational Methods: Jim Crutchfield
5:00-5:15	Discussion
5:30-7:00	Social Hour

THURSDAY, JULY 9

PART I:	FUNDAMENTAL CONCEPTS (Continued)
Morning	Chairperson: Ed Knapp
8:30-9:30 A.M.	Brian Arthur
9:30-9:45	Discussion
9:45-10:00	*Break*
10:00-11:00	Stuart Kauffman
11:30 A.M. -12:30 P.M.	Discussion, General and Groups
12:30	*Lunch*
PART II:	EXAMPLES OF COMPLEX ADAPTIVE SYSTEMS
	Talks are 45 minutes with 15 minutes for discussion
Afternoon	Chairperson: Chris Langton
1:15-2:15	Origins of Life: Steen Rasmussen
2:15-3:15	Evolution of Proteins: Tom Ray
3:15-3:30	*Break*
3:30-4:30	Protein Dynamics: Hans Frauenfelder
4:30-5:30	The Immune System: Alan Perelson

FRIDAY, JULY 10

PART II:	EXAMPLES OF COMPLEX ADAPTIVE SYSTEMS (Continued)
	Talks are 45 minutes with 15 minutes for discussion
Morning	Chairperson: Stuart Kauffman
8:30-9:30 A.M.	Developmental Complexity and Evolutionary Order: Brian Goodwin
9:30-10:30	Evolution of Individuality: Leo Buss/Walter Fontana
10:30-10:45	*Break*
10:45 A.M. -12:30 P.M.	Group Discussions
12:30	*Lunch*
Friday Afternoon Off	

SATURDAY, JULY 11

PART II:	EXAMPLES OF COMPLEX ADAPTIVE SYSTEMS (Continued)
	Talks are 45 minutes with 15 minutes for discussion
Morning	Chairperson: Murray Gell-Mann
8:30-9:30 A.M.	Evolution and Function of Mammalian Brain: Chuck Stevens
9:30-10:30	Cognition and Human Learning: Ben Martin
10:30-10:45	*Break*
10:45-11:45	How Do RNA and Viruses Explore Their World?: Peter Schuster
11:45 A.M. -12:30 P.M.	Group Discussions
12:30	*Lunch*
Afternoon	Chairperson: Murray Gell-Mann
1:15-2:15	How Neural Nets Work: Alan Lapedes
2:15-3:15	Adapting to Chaos: David Pines, Alfred Hubler
3:15-3:30	*Break*
3:30-4:30	Simulation of Complex Processes: John Holland
6:30-7:30	Cocktails and Tour of Sol y Sombra
7:30-9:00	Group Dinner
9:00-9:30	Explaining Complexity to Informed Laymen: Mitch Waldrop

SUNDAY, JULY 12

Sunday Morning Off	
PART II:	EXAMPLES OF COMPLEX ADAPTIVE SYSTEMS (Continued)
	Talks are 45 minutes with 15 minutes for discussion
Afternoon	Chairperson: Erica Jen
1:15-2:15 P.M.	Ecology: James Brown
2:15-3:15	General Discussion
3:15-3:30	*Break*
3:30-5:00	Discussion Groups

MONDAY, JULY 13

PART II:	EXAMPLES OF COMPLEX ADAPTIVE SYSTEMS (Continued)
	Talks are 45 minutes with 15 minutes for discussion
Morning	Chairperson: Brian Arthur
8:30-9:30 A.M.	Beyond General Equilibrium: Ken Arrow
9:30-10:30	Evolutionary Biology: John Maynard Smith
10:30-10:45	Break
PART III:	NON-ADAPTIVE SYSTEMS; SCALING; SELF-SIMILARITY; MEASURES OF COMPLEXITY
11:00-12:00 NOON	Measures of Complexity: Seth Lloyd
12:30	*Lunch*
Afternoon	Chairperson: To Be Announced
1:15-2:15	Non-Adaptive Systems: Erica Jen
2:15-3:15	Self-Organized Criticality: Per Bak

3:15-3:30	*Break*
PART IV:	REVISITATION
3:30-4:30	Review and Remarks, Theory. Round Table Discussion: David Pines, Chairperson
4:30-5:30	Review and Remarks, Applications: John Holland

TUESDAY, JULY 14

PART V:	GENERAL DISCUSSIONS, GROUP DISCUSSIONS, ROUND TABLES;
8:30 A.M. -5:30 P.M.	THEORY, APPLICATIONS, NON-ADAPTIVE SYSTEMS
5:30 -7:00	Social Hour

WEDNESDAY, JULY 15

PART V:	GENERAL DISCUSSIONS, GROUP DISCUSSIONS, ROUND TABLES;
8:30 -11:00 A.M.	THEORY, APPLICATIONS, NON-ADAPTIVE SYSTEMS (Continued)
11:00-11:30	Summary: Chairman

Roster for the Workshop on The Future of Supervised Machine Learning, August 6–7, 1992

Prof. Leo Breiman	University of California, Berkeley
Dr. Peter Cheeseman	NASA Ames Research Center
Mr. John Denker	AT&T Bell Laboratories
Prof. Thomas Dietterich	Oregon State University
Dr. Doyne Farmer	Prediction Company
Prof. David Haussler	University of California, Santa Cruz
Prof. Geoffrey Hinton	University of Toronto
Dr. Alan Lapedes	Los Alamos National Laboratory
Dr. Harry Martz	Los Alamos National Laboratory
Dr. Charlie Strauss	Los Alamos National Laboratory
Dr. James Theiler	Los Alamos National Laboratory/Santa Fe Institute
Dr. Naftali Tishby	AT&T Bell Laboratories
Prof. Grace Wahba	University of Wisconsin
Dr. Timothy Wallstrom	Los Alamos National Laboratory
Dr. David Wolpert	Los Alamos National Laboratory/Santa Fe Institute

Program for the Workshop on The Future of Supervised Machine Learning, August 6–7, 1992

THURSDAY, AUGUST 6, 192

The University House, Los Alamos National Laboratory

8:00 A.M.	Registration
8:15	David Wolpert, Santa Fe Institute/Los Alamos "Unifying the Formalisms Used in Supervised Learning"
9:15	Peter Cheeseman, NASA Ames Research Center "Advantages and Limitations of Bayesian Inference"
9:55	*Break*
10:25	Grace Wahba, University of Wisconsin, Madison "Generalization Error and the Bias-Variance Tradeoff, CV and GCV"
11:05	Naftali Tishby, AT & T Bell Laboratories Statistical Mechanics of Learning from Examples I: The High Temperature Limit"
11:45	*Lunch*
1:15 P.M.	Thomas Dietterich, Oregon State University "Solving Large-Scale Multi-Class Learning Problems Using Error-Correcting Output Code"
1:55	Leo Breiman, University of California, Berkeley "Current Research: Trees, Ramps, Regression"
2:35	*Break*
3:05	David Haussler, University of California, Los Angeles "How Well Do Bayes Methods Work for On-Line Prediction?"
3:45	John Denker, AT & T Bell Laboratories "Algorithmic Complexity Is Not Universal"
5:30	*Dinner* (David Wolpert's House)

FRIDAY, AUGUST 7, 1992

The Santa Fe Institute

7:30 A.M.	Breakfast at Santa Fe Institute
8:15	Bruce Abell, Santa Fe Institute "Overview of the Santa Fe Institute"
8:30	David Wolpert, Los Alamos/Santa Fe Institute "Why and Whither Supervised Learning"
9:10	Leo Breiman, University of California, Berkeley "Statistical Viewpoints"
9:50	*Break*
10:20	Peter Cheeseman, NASA Ames Research Center "Future Research Directions for Bayesian Inference"
11:00	Thomas Dietterich, Oregon State University "Concept Coverage as a Criterion for Optimal Learning Algorithms with Zero Prior Knowledge"
11:40	Geoffrey Hinton, University of Toronto "Simplifying Neural Networks by Soft Weight Sharing"
12:20 P.M.	*Lunch*
1:50	David Haussler, University of California, Los Angeles "Hidden Markov Models for Protein Families"
2:30	Grace Wahba, University of Wisconsin, Madison "Learning from Large-Scale Demographic Data Sets"
3:10	*Break*
3:40	Naftali Tishby, AT&T Bell Laboratories "Statistical Mechanics of Learning from Examples II: Types of Learning Curves"
4:20	John Denker, AT&T Bell Laboratories To Be Announced

Roster for the Workshop on Audification, October 28–30, 1992

Dr. James Ballas	Naval Research Laboratory
Dr. Robin Bargar	National Center for Supercomputing Applications
Dr. Aviv Bergman	Interval Research Corp.
Dr. Meera Blattner	Lawrence Livermore National Laboratory
Dr. Sara Bly	Xerox Palo Alto Research Center
Stephen Brewster	University of Calgary (temporary)
Mr. William Buxton	Computer Systems Research
Mr. Jonathan Cohen	Apple Computer
Prof. Nat Durlach	Massachusetts Institute of Technology
Tecumseh Fitch	Brown University
Dr. Bill Gaver	RANK Xerox EuroPARC
Matti Grohn	Center for Scientific Computing
Thomas Hanna	Naval Submarine Medical Research
Dr. Chris Hayward	Dallas, TX
Dr. Robert Hotchkiss	Los Alamos National Laboratory
Prof. Jay Alan Jackson	University of Southwest Louisiana
Mr. David Jameson	IBM T.J. Watson Research Center
Mr. Gregory Kramer	Clarity
Dr. Daniel Ling	Microsoft Corp.
Prof. David Lunney	University of North Carolina
Prof. Tara Madhyastha	University of Illinois
R. Kevin McCabe	Moffett Field
Elizabeth Mynatt	Georgia Institute of Technology
Albert Papp	Lawrence Livermore National Lab.
Mr. Roger Powell	Silicon Graphics
Tom Rettig	BroderbundSoftware
Dr. Carla Scaletti	Symbolic Sound Corporation
Dr. Stuart Smith	University of Massachusetts at Lowell
Dr. Daniel Steinberg	Sun Microsystems
Cheryl Wampler	Los Alamos National Laboratory
Dr. Elizabeth Wenzel	NASA Ames Research Center
Dr. David Wessel	CNMAT
Prof. Sheila Williams	University of Sheffield
Dr. Meg Withgott	Interval Research Corp.
Dr. George Zweig	Los Alamos National Laboratory

Program for the Workshop on Audification, October 28–30, 1992

WEDNESDAY, OCTOBER 28

8:30–9:00 A.M.	*Continental Breakfast*
9:00–9:15	Introduction by Santa Fe Institute
9:15–10:15	Self Introductions of participants
10:15–10:45	*Break*
10:45–11:10	Delivery of Information Through Sound: Overview and Effects of Context and Expectancy **Ballas**
11:10–11:15	Break
11:15 A.M.–12:30 P.M.	Some Organizing Principles for Representing Data with Sound **Kramer**

	Parameter Mapping in the Auditory Display of Data **Wessel**
12:30–1:30	*Lunch* (on premises)
1:30–2:10	Sound Synthesis Methods for Auditory Data Representations **Scaletti**
2:10–3:30	Time to look at hardware/software systems. (Including Scaletti w/Kyma, D. Wessel w/ demo of INDIGO synthesis software, and R. Powell w/ INDIGO sound tools.)
3:30–5:00	Audio Interpretation of Seismograms **Hayward**
	Informal discussion of auditory event classification in Sonar. **Hanna**
	Perceptual Principles in Sound Grouping **Williams**
5:00–6:30	Discussion on perception issues. Led by **Smith**
7:30	*Dinner* at a La Tertulia, 416 Agua Fria (Optional)

THURSDAY, OCTOBER 29

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:30	Auditory Display of Computational Fluid Dynamics Data **McCabe**
	Programming Foundations for a Multisensorial Environment **Hotchkiss**, Wampler and Zahrt
	Sound Probe: An Interactive Sonification Tool **Grohn**
10:30–11:00 Break	
11:00 A.M.–12:30 P.M.	Sonifying the Body Electric: Superiority of Auditory over Visual Display in a Complex, Multi-Variate System **Fitch** and Kramer
	Environments for Exploring Auditory Representations of Multidimensional Data **Smith**, Pickett and Williams
12:30–1:30	*Lunch* (on premises)
1:30–2:10	Parameterized Auditory Icons **Gaver**
2:10–3:00	Hardware/software look-ats (With Gaver, Bargar, and others.)
3:00–4:30	"Environmental Auditory Icons and Auditory Symbologies" and "Localization in Synthetic Acoustic Environments and Its Implications to Auditory Data Display" **Durlach** and **Wenzel**
	The Mercator Project: An Auditory Interface to X-Windows **Mynatt**
4:30–4:45	*Break*
4:45–6:00	Discussion on the state of the art and the state of the applications. (Who is doing what where and how well are they doing it. Contributions from researchers from hardware and software companies.) Led by **Buxton**

6:00–8:00	*Dinner*
8:00–10:00	A demonstration and discussion—What do we learn when several researchers sonify the same data? **Bly**
	Towards a common format-A discussion of data formats. **The Group**

FRIDAY, OCTOBER 30

8:30–9:00 A.M.	*Continental Breakfast*
9:00–10:30	Monitoring Background Activities **Cohen**
	Auditory Presentation of Gas-Phase Spectra Using Artificial Neural Networks for Functional Group Analysis McMillan, Morrison, **Lunney** and Gemperline
	Sonic Enhancements for Maps and Other Two-Dimensional Data **Blattner** and **Papp**
10:30–11:00	*Break*
11:00 A.M.–12:30 P.M.	Synchronization of Visual and Aural Parallel Program Performance Data **Jackson**
	Sonnet: Audio Enhanced Monitoring and Debugging **Jameson**
	A Framework for Sonification Design **Madhyastha** and Reed
12:30–1:30	*Lunch* (on premises)
1:30–2:00	System look-ats
2:00–3:00	Hierarchy and Pattern in Auditory Display **Bargar**
	Musical Structures in Data From Chaotic Attractors **Mayer-Kress**, Bargar, and Choi
3:00–3:30	*Break*
3:30–4:15	Audio Design for Consumer Software **Rettig**
	Desktop Audio at Sun **Steinberg**
4:15–5:30	Discussion on what do we do now. Led by **Kramer**

Roster for the Workshop on Approaches to Artificial Intelligence, November 6–9, 1992

Dr. Su-Shing Chen	National Science Foundation
Prof. Stephanie Forrest	University of New Mexico
Dr. Barbara Hayes-Roth	Stanford University
Prof. Richard Korf	University of California, Los Angeles
Dr. John R. Koza	Third Millennium Ventures
Prof. John Laird	University of Michigan
Prof. Victor Lesser	University of Massachusetts, Amherst
Prof. Hector Levesque	University of Toronto
Dr. Pattie Maes	Massachusetts Institute of Technology
Prof. Melanie Mitchell	Santa Fe Institute
Dr. Tom Mitchell	Carnegie Mellon University
Prof. Nils Nilsson	Stanford University
Prof. David E. Rumelhart	Stanford University
Prof. Yoav Shoham	Stanford University
Dr. Paul Smolensky	University of Colorado
Dr. David Waltz	Thinking Machines Corp.
Prof. Michael Wellman	University of Michigan

Program for the Workshop on Approaches to Artificial Intelligence, November 6–9, 1992

All sessions will take place at the Santa Fe Institute. The time allotted for each talk includes 45 minutes for the talk, 15 minutes for discussant's remarks and 15 minutes for participants' discussion.

FRIDAY, NOVEMBER 6

8:30–9:00 A.M.	*Continental Breakfast*
9:00–9:45	Welcome to SFI
	Introduction of Participants
	Welcome and Overview Nils Nilsson/David Rumelhart
	Welcoming Remarks from the National Science Foundation Su-shing Chen
Session 1: Symbol-Processing Approaches	
9:45–10:00	Overview To be Announced
10:00–10:15	*Break*
10:15–11:45	State-Space Searching Richard Korf
11:45 A.M.–1:15 P.M.	Declarative Knowledge Bases & Logical Reasoning Hector Levesque
1:15–2:15	*Lunch*
2:15–3:45	Blackboards Barbara Hayes-Roth
3:45–4:00	*Break*
4:00–5:30	SOAR John Laird (for Paul Rosenbloom)

SATURDAY, NOVEMBER 7

8:15–8:45 A.M.	*Continental Breakfast*	
Session 2: BioComputation Approaches		
8:45–9:15	Overview	
		David Rumelhart
9:15–10:30	Connectionist AI	
		Paul Smolensky
10:30–10:45	*Break*	
10:45–12:00 NOON	Genetic Algorithms	
		John Koza
12:00–12:45 P.M.	*Lunch*	
12:45–2:00	"Situated" Artificial Creatures	
		Pattie Maes
2:00–2:15	*Break*	
2:15–3:30	Real-Time Learning and Control	
		Andy Barto
7:45	*Group Dinner* at Fabio's, 227 Don Gaspar	

SUNDAY, NOVEMBER 8

8:30–9:00 A.M.	*Continental Breakfast*	
Session 3: Heterogeneous Approaches		
9:00–9:30	Overview	
		Victor Lesser
9:30–10:45	Distributed Artificial Intelligence	
		Victor Lesser
10:45–11:00	*Break*	
11:00 A.M.–12:15 P.M.	Economics-Based Methods	
		Mike Wellman
12:15–1:00	*Lunch*	
1:00–2:15	Massive-Parallelism	
		David Waltz
2:15–2:30	*Break*	
2:30-3:45	Agent-Oriented Programming	
		Yoav Shoham

MONDAY, NOVEMBER 9

8:30–9:00 A.M.	*Continental Breakfast*	
Session 4: Integrative Approaches		
9:00–9:30	Overview	
		Nils Nilsson
9:30–10:45	Integrated Robots	
		Tom Mitchell
10:45–11:00	*Break*	
11:00 A.M.–12:15 P.M.	Integrated Agents	

John Laird

12:15–2:00 p.m. *Lunch/General Discussion*

Roster for the Working Group on Computation, Dynamical Systems, and Learning, November 16–20, 1992

Jim Crutchfield	University of California, Berkeley
Jim Hanson	University of California, Berkeley
Melanie Mitchell	University of Michigan/SFI
Steve Omohundro	International Computer Science Institute
Jordan Pollack	Ohio State University

Program for the Working Group on Computation, Dynamical Systems, and Learning, November 16–20, 1992

All talks will take place at the Santa Fe Institute at 9:30 A.M. Each talk will be followed by a discussion period and lunch for participants at noon.

MONDAY, NOVEMBER 16, 1992

9:30 A.M. "Revisiting the Edge of Chaos: Evolving Cellular Automata to Perform Computational Tasks"
Melanie Mitchell, Santa Fe Institute

TUESDAY, NOVEMBER 17

9:30 A.M. "Innovation, Induction, and Complexity"
Jim Crutchfield, UC Berkeley

WEDNESDAY, NOVEMBER 18

9:30 A.M. "Chaotic Pattern Bases for Cellular Automata"
Jim Hanson, UC Berkeley

THURSDAY, NOVEMBER 19

9:30 A.M. "Cognition as a Complex System"
Jordan Pollack, Ohio State University

FRIDAY, NOVEMBER 20

9:30 A.M. "Learning and Recognition by Model Merging"
Steve Omohundro, International Computer Science Institute

1992 PUBLIC LECTURES

Christopher Langton, Los Alamos National Laboratory
"Artificial Life"

Steve Lansing, University of Southern California
"The Goddess and the Computer (Balinese Water Temples)"

Tom Furness, University of Washington
"Virtual Reality"

Joshua M. Epstein, The Brookings Institution and Princeton University
"Complex Systems, Nonlinear Dynamics, and Global Welfare"

John Maynard Smith, University of Sussex at Brighton
"Major Transitions in Evolution"

Tom Ray, University of Delaware
"Virtual Life: Evolution of Digital Organisms"

Murray Gell-Mann, California Institute of Technology
"Getting Creative Ideas"

DATE FILMED

9/9/93

END